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RISK ANALYSIS AND MANAGEMENT OF DIVING OPERATIONS: ASSESSING HUMAN FACTORS

by

Timothy C. Liberatore

November 20, 1998

Safety
DSMAS
FIRST

Supervised by

Professor Robert G. Bea

Ocean Engineering Graduate Program

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Submitted in Partial Satisfaction of the Requirements for

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ABSTRACT

Current technological advancements in diving systems have been paramount to increasing the depth and duration of commercial and military diving operations. Even with such advances and the use of proven engineered diving systems, as humans continue to strive for deeper and longer dives, significant risk to all personnel is inherent. Minimization and mitigation of such risk is vital to meet the need for continued use of manned-diving systems to perform specific underwater tasks.

This paper will focus on developing mixed qualitative and quantitative risk analysis tools using current human and organizational factors (HOF) research and database software that can be applied to diving operations. Surprisingly, assessment, evaluation, and management of risks associated with diving operations are rarely performed even in today's high-tech environment. Since a major component of the diving operation is the human and organizational element, there should be adequate safety management systems in place to assess their likelihood of failure. Assessment and monitoring are vital to ensure safe procedures in diving operations and require effective operator/diver involvement and training.

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1.0 INTRODUCTION

The combination of a hazardous environment and modern technology can often magnify the effects and consequences of performing simple tasks. This is the case when performing work in an austere, almost alien, underwater environment while using "leading-edge" technological diving systems. Underwater work, by its nature, can therefore be considered as inherently risky business. Unfortunately, there is still a need for manned-diving systems to perform specific tasks that remotely operated vehicles (ROV) and submersibles are unable to perform. As such, human and organizational factors (HOF) and the man-machine interface must be considered when evaluating the risks associated with a diving operation.

The human element, can be considered "the limiting and the enabling factor in offshore operations, depending on one's perspective, and depending on the availability of tools to support and maximize performance" [Kirwan, 1997]. It is this double-edged sword that has apparently kept manned-diving systems as the tool of choice for performing complex underwater work and any tasks requiring manual-dexterity (e.g. underwater welding, concrete placement, and pipeline repair). Like any other component in a system, the human element is complex and interacts with the other system components with significant uncertainty.

This paper will discuss HOF applied to diving systems and operations, and proceed with the development of a fully integrated diving safety management and

assessment system that draws upon recent developments in HOF assessment and incorporates incident/accident-reporting legislation. The results will hopefully help offshore diving operators, both military and commercial, in their quest to minimize and mitigate the risks and uncertainty that are inherent to manned-diving and underwater operations.

2.0 LITERATURE REVIEW

2.1 Risk Assessment, Evaluation, and Management

Risk assessment and management techniques have been successfully applied in the fields of aerospace, nuclear and chemical engineering for the last two decades. In the aftermath of the Space Shuttle Challenger accident in 1986, NASA formally established the Safety, Reliability, and, Maintainability, and Quality Assurance Office (SRM&QA) to specifically implement risk management programs. Risk management is defined as a "comprehensive process for dealing with risk in a decision-making framework to provide for the identification and evaluation of significant risks, and their rational acceptance or optimal mitigation" [Philipson and Buchbinder, 1997].

Risk assessment and management has two important steps. The first part is the determination of the risks associated with the system and the second part involves determination of acceptability of those risks [Bea, 1998]. "In safety, risk is the product of the frequency of an unwanted event and the consequences of that unwanted event" [Harrison, 1997]. Harrison [1997] further outlined the complete process of risk management for marine systems in the following eight steps:

1. Define the activity and its scope (what is at risk?);
2. Identification of hazards and risks;
3. Assess the risk;

4. Control the risk (as appropriate by elimination or reduction);
5. Monitor and review (follow the success);
6. Contingency plans (actions to take in the event of unwanted change);
7. Defining management responsibilities;
8. Emergency preparedness (real-time crisis management).

This process of risk management has been adapted and applied to diving systems and operations as shown in Figure 1 on the following page [Monioudis and Mavromatakis, 1997]. Key elements in this process are the frequency of event's database and the final step, initiation of management change. These steps are critical to continuous improvement of the system and in the case of diving operations are areas that could use significant improvement. Development of this database management system drawing from recent methods in HOF studies and integrating the required safety reporting legislation is paramount to continued use of manned-diving operations.

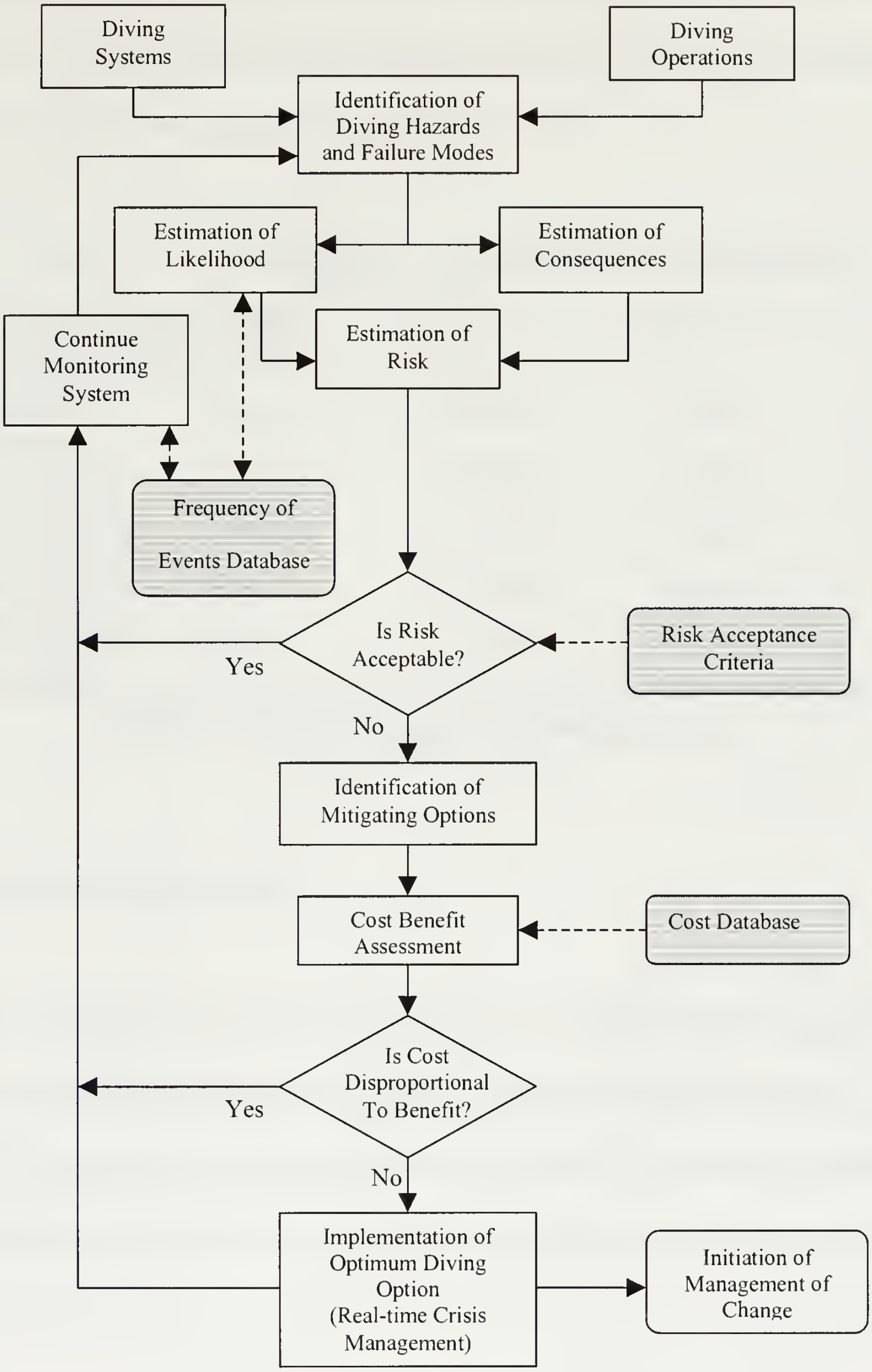

Diving Systems
Diving Operations
Identification of Diving Hazards and Failure Modes
Estimation of Likelihood
Estimation of Consequences
Continue Monitoring System
Estimation of Risk
Frequency of Events Database
Is Risk Acceptable?
Yes
No
Risk Acceptance Criteria
Identification of Mitigating Options
Cost Benefit Assessment
Cost Database
Is Cost Disproportional To Benefit?
Yes
No
Implementation of Optimum Diving Option (Real-time Crisis Management)
Initiation of Management of Change

Figure 1: Risk Management Process [adapted from Monioudis and Mavromatakis, 1997]

As a basis for determining the cost benefit, Table 1 provides a database for comparison of the costs and limitations of the various systems associated with diving operations [Offshore, 1983], [Navy Diving Manual, 1993].

Category	*Working Depth (ft)*	*Capital Investment*	*Daily Rate (approx.)*
SCUBA Diving (Air)	0-190	Low	Low
Surface Supply Diving (Air or Heliox)	0-190	Low	Low
Bounce Diving (2-diver system)	190-300	$300,000	$10,000
Bounce Diving (4-diver system)	190-300	$600,000	$13,000
Saturation Diving (4-diver system)	190-1000	$1-5 million	$16,000
Saturation Diving (4-diver system)	190-1000	$1-5 million	$20,000
One-Atmosphere (Jim, Wasp)	2,000	$600,000	$2,000

Table 1: Manned Diving Limitations and Costs

2.2 Reliability and Risk Analysis

Risk analysis involves the evaluation of the sources, effects, and consequences of risks [Bea, 1994]. It can be qualitative and/or quantitative or a mixture of the two. The reliability of a system (P_s) is the probability that the system will perform successfully, while the probability of failure (P_f) is the likelihood that the system will fail given by Equation (1) [Bea, 1998].

$$P_f=1-P_s \tag{1}$$

In this paper, failure of a diving system will be defined as the likelihood of injury to a diver. Although most occupational databases are concerned with the fatality rates, an effective safety management database for the diving industry should account for all incidents, accidents, near misses, and initiating events leading up to the incident.

2.2.1 Qualitative Risk Analysis

A qualitative risk analysis is a subjective evaluation of the system based on previous accidents and determination of the most common failure modes, known as a coarse analysis. Once the failure modes are determined a detailed qualitative analysis can be performed to estimate the consequences and likelihood of the failure modes. The Failure Mode and Effect Analysis (FMEA) is a common method for this type of assessment [Aven, 1992]. Most diving safety management systems only make use of this type of risk analysis, often referred to as an activity hazard analysis.

With the Lord Cullen inquiry report into the Piper Alpha offshore disaster, all offshore operators are recommended to describe their Safety Management Systems as part of a “Safety Case” for installations [UK DOE, 1990]. The report states that the Safety Management System should be adequate to ensure safe operation of the installation and it’s equipment and based on the principles of a quality management system. An additional requirement of the report is auditing and monitoring of the contractor’s safety programs [Wood, 1991]. According to Wood [1991], this level of analysis and proactive safety management along with a Diving Procedures Manual has

contributed to a reduction of accidents and incidents in the North Sea by 78% since 1989. Projects implementing this approach had overall incident rates lower than those that simply used operator requirements.

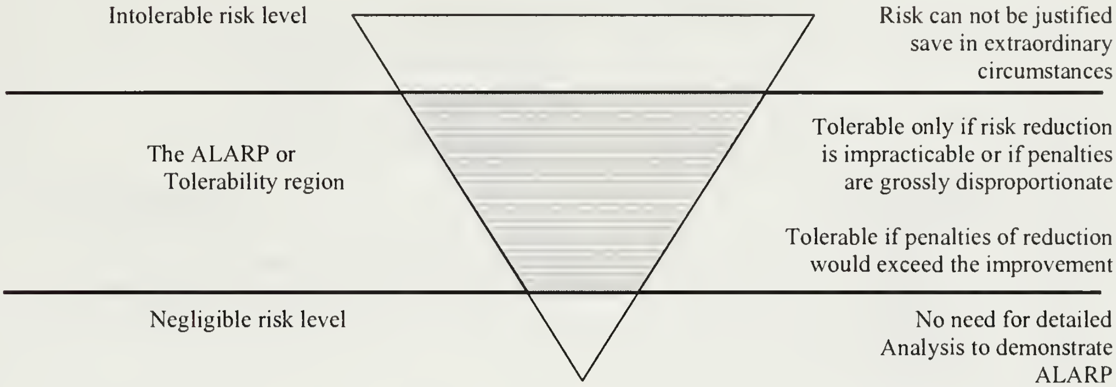

Intolerable risk level
Risk can not be justified save in extraordinary circumstances
The ALARP or Tolerability region
Tolerable only if risk reduction is impracticable or if penalties are grossly disproportionate
Tolerable if penalties of reduction would exceed the improvement
Negligible risk level
No need for detailed Analysis to demonstrate ALARP

Figure 2: The ALARP Principle [from Lamb and Rudgley, 1997]

The objective and cornerstone of such a qualitative hazard analysis is to ensure that all significant hazards are identified and that the level of risk for each is determined to be "As Low as Reasonably Practicable". This principle, known as ALARP, is shown in Figure 2 [Lamb and Rudgley, 1997]. Determination of what is considered ALARP is subject to past acceptable risk criteria and may not be adequate for today's standards.

To better address this ALARP principle and assist in the detailed qualitative risk assessment of the various diving failure modes, a Risk Assessment Code (RAC) matrix adopted from the U.S. Navy [OPNAVINST 3500]. From this matrix, one can quickly estimate and determine the high consequence with moderate to low probability hazards which are of considerable concern and likely to require a more in-depth assessment [Bea,

1998]. Table 2 shows the RAC matrix, which is a combination of the hazard severity and the loss probability.

RAC		*Probability*			
		A	*B*	*C*	*D*
Hazard Severity	I – Diver Fatality	1	1	2	3
	II – Severe Injury	1	2	3	4
	III – Minor Injury	2	3	4	5
	IV – Negligible	3	4	5	5

Loss Probability:
A – Likely to occur frequently (1E-1)
B – Probably will occur or expected to occur several times (1E-2)
C – May occur or can be reasonably expected to (1E-3)
D – Unlikely to occur (1E-4)

RAC Definition:
1 – Critical
2 – Serious
3 – Moderate
4 – Minor
5 – Negligible

Table 2: Risk Assessment Code (RAC)

2.2.2 *Quantitative Risk Analysis*

Once the critical failure modes have been determined, a quantitative or objective analysis of the diving system can be performed. This approach generally makes use of numerical variables and probabilistic models, and traditionally known as probabilistic risk analysis (PRA) or quantified risk analysis (QRA) using a Fault Tree Analysis or Event Tree Analysis [Bea, 1998]. This type of analysis has been developed in-depth for various marine systems, but has unfortunately fallen short in integrating the human and organizational elements.

2.2.3 Mixed Qualitative and Quantitative Analysis

The third approach to risk analysis, referred to as a mixed qualitative and quantitative analysis, can best be described as a process where "linguistic variables are translated to numerical variables" [Bea, 1998] as shown by Figure 3 [Bea, 1996]. Without sufficient and reliable human error databases, this approach offers the best method to assess the influence of human and organizational factors.

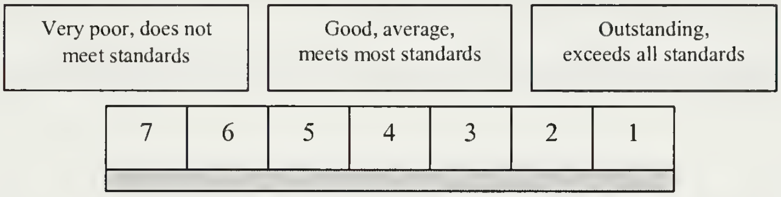

Very poor, does not meet standards
Good, average, meets most standards
Outstanding, exceeds all standards
7
6
5
4
3
2
1

Figure 3: Mixed Qualitative & Quantitative Grading Analysis [from Bea, 1996]

2.3 Human and Organizational Factors (HOF) in Reliability

Since the diving system and operation are primarily a man-machine interface, it is critical to understand the human component of the system to determine the overall system reliability. Extensive research has been conducted on identification of the causes of marine related accidents. According to most experts, human and organizational factors (HOF) are the cause of approximately 80% of offshore and marine accidents. Det Norske Veritas produced the following statistics related to causes of offshore accidents: 77%

were related to human unreliability and only 23% were related to technical causes [ISM Code Workshop, 1997].

In this paper, human reliability is defined as the probability of accomplishing a job or task successfully while human error is the failure to carry out a specified task that could lead to an accident [Gertman and Blackman, 1993]. To assist in the estimation and quantification of human error, Swain and Guttman [1983] developed generic human error rates from experiment and simulation in the operations of nuclear power plants as shown in Figure 4. In addition to these human error rates, Dougherty and Frangola [1988] conducted further experiments and simulations to develop *performance shaping factors* which are used as multipliers to the mean human error rates, shown in Table 3.

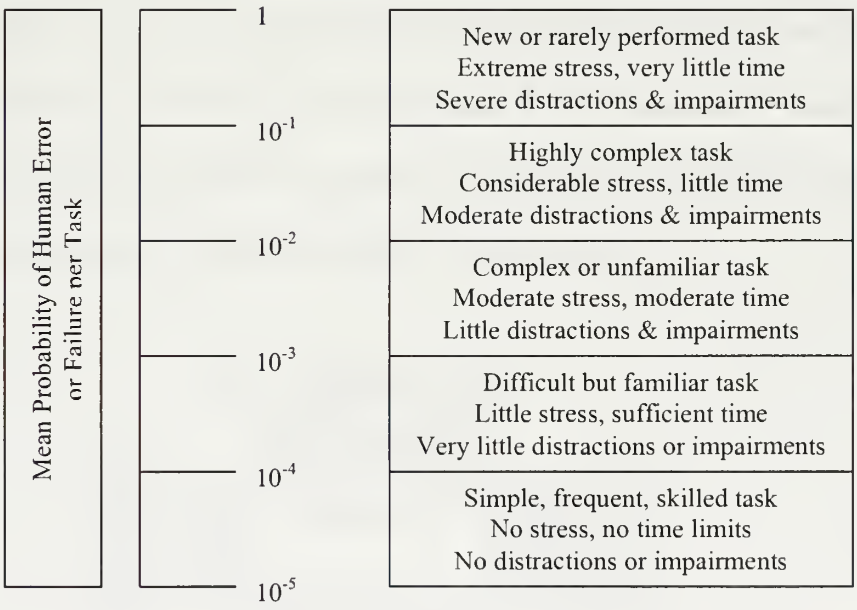

Mean Probability of Human Error or Failure per Task
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
New or rarely performed task
Extreme stress, very little time
Severe distractions & impairments
Highly complex task
Considerable stress, little time
Moderate distractions & impairments
Complex or unfamiliar task
Moderate stress, moderate time
Little distractions & impairments
Difficult but familiar task
Little stress, sufficient time
Very little distractions or impairments
Simple, frequent, skilled task
No stress, no time limits
No distractions or impairments

Figure 4: Generic Human Task Error Rates

Error Producing Condition	Multiplier	**Error Producing Condition**	Multiplier	**Error Producing Condition**	Multiplier
Unfamiliarity	17	Performance ambiguity	5	Lack of exercise	1.8
Time shortage	11	Misperception of risk	4	Unreliable instruments	1.6
Low signal to noise ratio	10	Poor feedback	4	Absolute judgements required	1.6
Features over-ride allowed	9	Inexperience	3	Unclear allocation of functions	1.6
Spatial / functional incompatibility	8	Communication filtering	3	Lack of progress tracking	1.4
Design model mismatch	8	Inadequate checking	3	Limited physical capabilities	1.4
Irreversible action	8	Objectives conflicts	3	Emotional stress	1.3
Information overload	6	Limited diversity	2.5	Sleep cycle disruption	1.2
Technique unlearning	6	Educational mismatch	2		
Knowledge transfer	5.5	Dangerous incentives	2		

Table 3: Performance Shaping Factors

According to Gertman and Blackman [1993], "hardware failure and human failure equals system failure", but "there is a synergy between the two where human actions can either aid or impede recovery". "Optimizing the human-machine interface" can often reduce risk. Therefore, to properly assess and evaluate the risks associated with diving systems and operations, the author will attempt to integrate human reliability analysis (HRA) with the system probabilistic risk analysis (PRA) process.

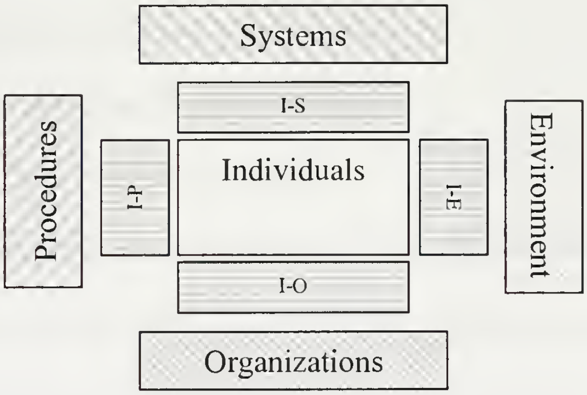


Figure 5: Components and Interfaces leading to Human Errors [from Bea, 1994]

Bea [1994] identified the components and interfaces that can lead to human errors as shown in Figure 5. Individual operators can be influenced to make errors by their organization, procedures (formal and informal), systems and hardware, and the environment. In addition, Bea [1994] classified the specific malfunctions related to the individual and organization. Individual malfunctions consisted of:

1) Communications;
2) Slips (accidental lapses);
3) Violations (infringement, transgression);
4) Ignorance (unawareness, unlearned);
5) Planning and preparation (program, procedures, readiness);
6) Selection and training (suited, education, practiced);
7) Limitations and impairments (fatigue, stressed, diminished senses); and
8) Mistakes (cognitive errors).

Similarly, the malfunctions associated with organizations consisted of:

1) Communications;
2) Culture (goals, incentives, values, trust);
3) Violations (infringement, transgression);
4) Ignorance (unawareness, unlearned);
5) Planning and preparation (program, procedures, readiness);
6) Structure and organization (team integrity, interdependence);
7) Monitoring and controlling (awareness, correction); and
8) Mistakes (cognitive errors).

Calculation of human and organizational error (HOE) can be done by the use of Equations (2) and (3), the probability of failure of the system to develop quality attribute (i), $P(F_{Si})$, where (I) represents intrinsic causes (such as extreme environmental conditions and other similar inherent, natural, or professional uncertainties) and (E) represents extrinsic causes due to HOE [Bea, 1998].

$$P(F_{Si}) = P(F_{SiI} \mid E_{Si})\, P(E_{Si}) + P(F_{SiI} \mid \cancel{E}_{Si})\, P(\cancel{E}_{Si}) + P(F_{SiE} \mid E_{Si})\, P(E_{Si}) \qquad (2)$$

Where,

$$P(\cancel{E}_{Si}) = 1 - P(E_{Si}) = \textit{probability of no HOE} \qquad (3)$$

And, $P(A \mid B)$ represents the probability of occurrence of A conditional on the occurrence of B.

For diving operations, the quality attribute (i) is *Safety*, and the primary concern and dominant factor of the equation is the probability of HOE due to extrinsic causes $P(F_{SiEj})$ during the operation (j=3) phase. The diving operation can be further broken down into various phases, each of which $P(F_{SiEjk})$ can be influenced by the eight types of human and organizational malfunctions given previously, resulting in $P(F_{SiEjkm})$.

The HOE can be reduced by proper quality control and quality assurance (QC/QA), provided by the dive buddy, standby diver or surface support. Assuming independent detection and correction activities, $P(F_{SiEjkm})$ can be replaced by Equation (4), where P(D) is the probability of detection and P(C) is the probability of correction.

$$P(UE_m) = P(E_m)[1 - P(D_m)P(C_m)] \tag{4}$$

The study of human and organizational factors seeks to improve safety through reduction of the frequency of human errors and mitigating the consequences of human errors when they occur. During an offshore diving operation, the results of human or organizational errors can lead to "catastrophic consequences" [Blumenberg, 1996]. To minimize these consequences, a method of assessment should be adopted that adequately evaluates the likelihood of failures and ultimately determines the risk associated with all components of the system.

2.3.1 Aviation HOF Checklists

The study of "Human Factors" involves an application of scientific methods and technology to solve human performance problems. It represents an attempt to "optimize the performance of individuals in systems operation, maintenance, and supervisory control of complex environments exemplified by today's sophisticated aircraft and support equipment and facilities" [Ciavarelli, 1997]. From a systems point of view, performance and reliability can be improved by focusing on reduction of human error. This can be done by concentrating efforts to insure that design of equipment and procedures are adequate, and that personnel selected for the task have the required capabilities and competencies, or can be taught them.

To better understand the influence of HOF in man-machine systems, various HOF checklists for the aviation community have been developed and can be reviewed in the annual proceedings of the Human Factors Society and Aviation Psychology Symposia, and International Society of Accident Investigators. These checklists provide a quick, and to a large degree, a valid and adequate assessment method for identifying areas to improve a system's reliability. Most notably, Ciavarelli [1997] of the Naval Postgraduate School has developed a more accurate and "user-friendly" human factors checklist for aviation.

The approach used in developing this form was based on analyzing hundreds of aviation accidents and then "classifying particular human errors, or error prone conditions, under the rubric of specific human performance categories (Sensory-Perceptual, Medical-Physiological. Knowledge-Skill, Personality-Safety Attitude, Decision-Judgement, Crew Communication-Coordination, System Design, and Organizational-Supervisory)" [Ciavarelli, 1997]. A portion of the resulting Human Factors Checklist from the Naval Aviation Safety School, Naval Postgraduate School is provided as Appendix A. The complete version of this checklist can be obtained from the following World Wide Web address: http://web.nps.navy.mil/~avsafety/pub/hfchklst.htm.

Although these HOF checklists are a step in the right direction to enhance safety, they are still deficient in capturing qualitatively and quantitatively the risk or uncertainty associated with systems involving HOF. The checklists are usually Yes/No questions and are purely subjective. In addition, most checklists can not offer advice on the relative

importance of each checklist item, nor do they take into account the context in which the system is being used [Kirwin, 1998].

2.3.2 Diving HOF Checklist

Although human factors analysis may be relatively straightforward under normal working conditions, in an underwater environment of "high density, low temperatures, increased turbidity, reduced visibility, currents, and potential marine hazards, the evaluation becomes far more challenging" [Crosson, 1993]. Design, development, and operation of diving systems must consider all of these factors. In addition, consideration must be given to the diver's physiological requirements, efficient performance of the system in all scenarios, and adequate safety and comfort for the divers.

According to most diving accident statistics [Naval Safety Center, 1996 and Diver Alert Network, 1996], the majority of accidents occur during the diving operations phase. To assist with safety assessment during this phase, Blumenberg [1996] developed a dive team HOF checklist (see Appendix B). The dive team human factors checklist is intended for "observations of real-time operations and facilitation of recording targeted behaviors" [Blumenberg, 1996]. The checklist provides a quick and user-friendly assessment form for analyzing HOF in real-time diving operations utilizing a 1.0 (poor) to 4.0 (outstanding) scoring system. Like the aviation HOF checklist, it is a step in the right direction towards developing a HOF error database.

Blumenberg [1996] used the dive team HOF checklist as a post-accident investigation of a diving fatality of an underwater construction worker assigned to the U.S. Navy. The results showed where human factors acted as contributing and compounding events and later lead to the eventual fatal accident. Although the assessment was limited by witness accounts instead of actual observations, it revealed that HOF factors received a range of scores from poor (performance significantly below expectations) to standard (demonstrated behavior promotes and maintains team effectiveness). No category received the high score of 4 which equates to an outstanding (performance represents exceptional skill in the application of specific behaviors, and serves as a model for teamwork).

Table 4 below shows the summary of scores for this accident.

	Pre-Dive	**Dive**	**Post-Dive**
Team communication & coordination	2.0	N/A	N/A
Situational awareness & decision making	1.8	2.0	2.0
Auditing	N/A	1.0	N/A
Resources	2.7	2.7	2.5
Operational procedures	3.0	3.0	3.0
Training	N/A	2.0	N/A
Individual fitness of diver	2.1	2.0	2.0
Special situations	2.0	2.0	3.0
Overall observation	N/A	N/A	N/A

Table 4: Score Summary from Dive Team HOF Checklist [Blumenberg, 1996]

From this quick assessment, a safety/dive supervisor could have quickly determined that the areas of concern noted with a score of 1 or 2 (e.g. communications, auditing, decision-making, training, fitness, and special situations) should have been analyzed in more depth and warranted further examination. In this situation, the diving operation would have been ceased due to its overall low scoring equating to significantly high risk for the divers.

3.0 CURRENT DIVING SAFETY MANAGEMENT

3.1.1 Military and Government Diving Safety Management

Within most military and government-sponsored diving organizations, safety is managed through various planning and safety checklists and a simplified activity risk analysis. The safety and planning checklist used by the U.S. Navy consists of the following detailed sections [U.S. Navy Diving Manual, 1993]:

a) Analyze the mission for safety,
b) Identify and analyze potential hazards,
c) Select equipment, personnel, and emergency procedures, and
d) Establish safe diving operational procedures.

In addition, there are various operations checklists for the different types of diving systems selected, such as a surface-supplied diving operation checklist. The activity risk analysis usually only involves identification of potential hazards (again through a simple checklist) and steps to mitigate those hazards. It does not however provide adequate in-depth analysis of the likelihood of events and the consequences of those events, nor does it analyze the impact of human and organizational factors (HOF). It is this area of concern that should be qualitatively and quantitatively analyzed through a database managed safety information system.

The U.S. Navy also uses a relatively simple reactive approach to diving safety that requires the submission of an accident/incident report to the Naval Safety Center. According to the U.S. Navy Diving Manual [1993], an accident is "an unexpected event, which culminates in loss of or serious damage to equipment or injury to personnel". An incident is "an unexpected event which degrade safety and increases the probability of an accident. The accident/incident information sheet is included as Appendix C for reference purposes. It provides a starting point for development of a detailed assessment form, which will account for HOF and near-mishaps.

Although the Naval Safety Center diving statistics [1996] show the number of diving accidents/incidents as low compared to the total number of dives conducted each year, there is no database managed system in-place which accurately tracks the incident rates. Additionally, there is a significant deficiency with current safety management systems since they due not adequately assess the initiating, propagating, or contributing HOF events leading to the incident.

3.1.2 Commercial Diving Safety Management

In the commercial industry, the primary means of managing diving safety, whether inshore or offshore, is through the Association of Diving Contractors' (ADC) "Consensus Standards for Commercial Diving Operations". It provides a standard of safe practices and procedures for diving operations to complement applicable governmental rules and regulations. It also provides detailed information regarding

personnel requirements, operations procedures, equipment and systems, and accident reporting [ADC, 1992]. It does not however provide any specific guidelines or systematic procedures for managing and assessing safety on a day-to-day basis.

The most significant part of the ADC Consensus Standard, which is applicable to developing a diving safety management system, relates to accident reporting. Although this is a reactive approach to safety management, it is a section that can be further developed and used during a follow-up phase to create a HOF error database. Incident rates are determined by Equation (5) and reported to Occupational Safety and Health Administration (OSHA) via the ADC *Standard Incident Data Reporting Form* (see Appendix D).

$$Incident\ Rate = \frac{\#\ of\ Incidents \times 200{,}000}{Hours\ worked} \tag{5}$$

This incident rate represents the total number of incidents equated to one hundred employees working forty hours per week for a fifty-week year. The incident rate is calculated for Lost Time Accidents (LTA) and Total Reportable Incidents. A LTA is a work-related accident or illness that results in the worker being unable to perform any work for 24 hours or more after the incident. A reportable incident is usually a work-related accident or illness that requires treatment by a Licensed Physician [ADC, 1992]. Type I decompression sickness (DCS-I: pain only bends), where offshore treatment is successful, is non-reportable. Type II decompression sickness (DCS-II: serious symptom

bends) is reportable if shore hyperbaric treatment occurs. This incident rate will be included in the proposed Diving Safety Management System discussed later.

Since the beginning of 1991, a Diving Safety Management System has been in successful use by a major North Sea offshore operator [Wood, 1991]. The system was developed in response to diving accident statistics published by the United Kingdom Department of Energy. The statistics revealed that between 1976 to 1988 diving activity produced an average of 13% of the serious injuries that occurred offshore. The system sets out criteria for safe management of diving operations in proven, formal and consistent management control systems. The complete system has the following objectives:

1) To enable the identification and use of competent and safe contractors.
2) To encourage contractors to develop safety management systems.
3) To reduce the potential for accidents before offshore work commences.
4) To assist in the development of safe and cost effective diving safety policies and procedures.
5) To encourage the use of formal hazard evaluation systems.
6) To ensure that all criteria, standards, guidelines, and legislation are considered where applicable.
7) To provide clear and concise responsibilities, objectives, and policies for all personnel involved in diving operations.

The most significant part of the diving safety management system outlined by Wood [1991] is the contractor safety evaluations. There are two types of evaluations that are carried out, 1) contractor safety evaluation of documented safety policies and effectiveness and 2), safety performance evaluation of the actual job safety performance. The evaluations are conducted through a mixed qualitative/quantitative assessment where elements of safety are given a score from 0 to 10. Although this system is an audit for determining whether or not a contractor should be put on a bidder list, it provides a framework for assessments and inspections that can be carried out by the individual contractors. It is by far the first step toward a proactive assessment system to minimize risk in the offshore diving industry.

After work is completed, the contractors are evaluated on the following items and disciplines:

1) Hazard control: housekeeping, certification, general hazard control, maintenance of plant and equipment, permit to dive procedures.
2) Fire control and industrial hygiene: chemical hazard control, flammable materials and equipment control, fire control measures, chamber waste and trash control.
3) Supervisory and safety participation: supervisor safety training, safety instruction of new employees, safety meetings, safety audits and inspections, supervisor/diver safety contact, emergency drills, accident and incident investigation [Wood, 1991].

3.2 A Mixed Qualitative and Quantitative Assessment of HOF

The complimentary approach to risk analysis discussed earlier, a mixed qualitative and quantitative analysis, can best be described as a process where "linguistic variables are translated to numerical variables" [Bea, 1998] as shown in Figure 3 [Hee and Bea, 1997]. Without sufficient and reliable human error databases, this approach offers the best method to assess the influence of human and organizational factors in the offshore industry.

Assessment of HOF in the entire life cycle of the diving system and operation is beyond the scope of this paper. Instead, the mixed qualitative/quantitative assessment method discussed will be applied to system safety concerns during the operations phase as shown in Figure 6. Extrinsic causes have been related to 80% of marine accidents and it is during the operations phase where the majority of accidents occur [Bea, 1998].

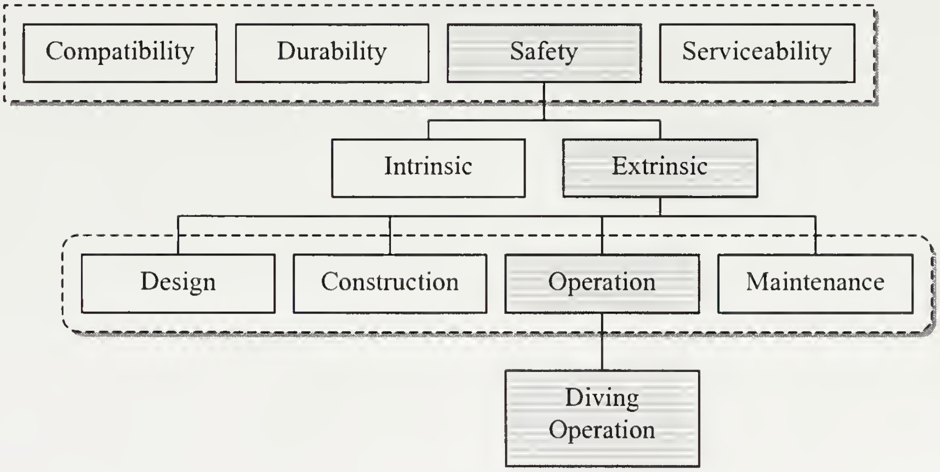


Figure 6: Life-Cycle Evaluation of HOF in Diving Operations

The diving statistics indicate that decompression sickness (DCS) and arterial gas embolism (A.G.E.) are the greatest concerns and the result of most incidents. Both of these incidents occur in the ascent and decompression phases of the diving operation shown in Figure 7. In addition, the statistics also indicate that the loss of air supply should also be focused on, which again would usually occur during ascent and decompression or at the end of the bottom operation.

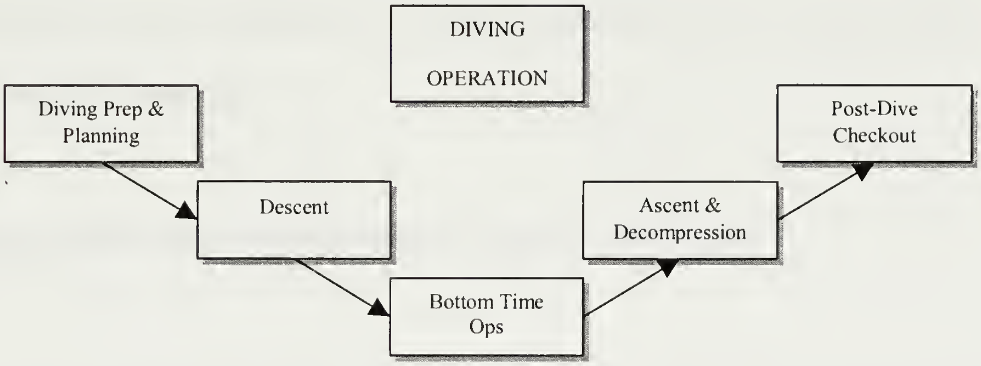


Figure 7: Diving Operation

4.0 DIVING SYSTEMS/OPERATIONS

A diving system represents the entire plant and equipment necessary to conduct the diving operation. In accordance with International Maritime Organization (IMO) [Code of Safety for Diving Systems, 1995], these diving systems should be "designed to minimize human error and be constructed so that failure of any single component (determined, if necessary, by an appropriate risk assessment) should not lead to a dangerous situation". A brief synopsis and simplified system diagrams of the primary diving systems used by commercial and military diving organizations are provided to assist in the risk assessment.

4.1 Self-contained Underwater Breathing Apparatus (SCUBA)

The self-contained underwater breathing apparatus (SCUBA) diving system is the most common system in use. A system diagram is shown in Figure 8. SCUBA, although readily available and easy to use, has significant areas for safety concern.

1) Lack of communications (except for hand signals),
2) Use of a buoyancy compensator (BC),
3) Lack of air source redundancy unless using an emergency breathing system (EBS) or bailout,
4) Time constraint based on tank capacity, and
5) Decompression concerns.

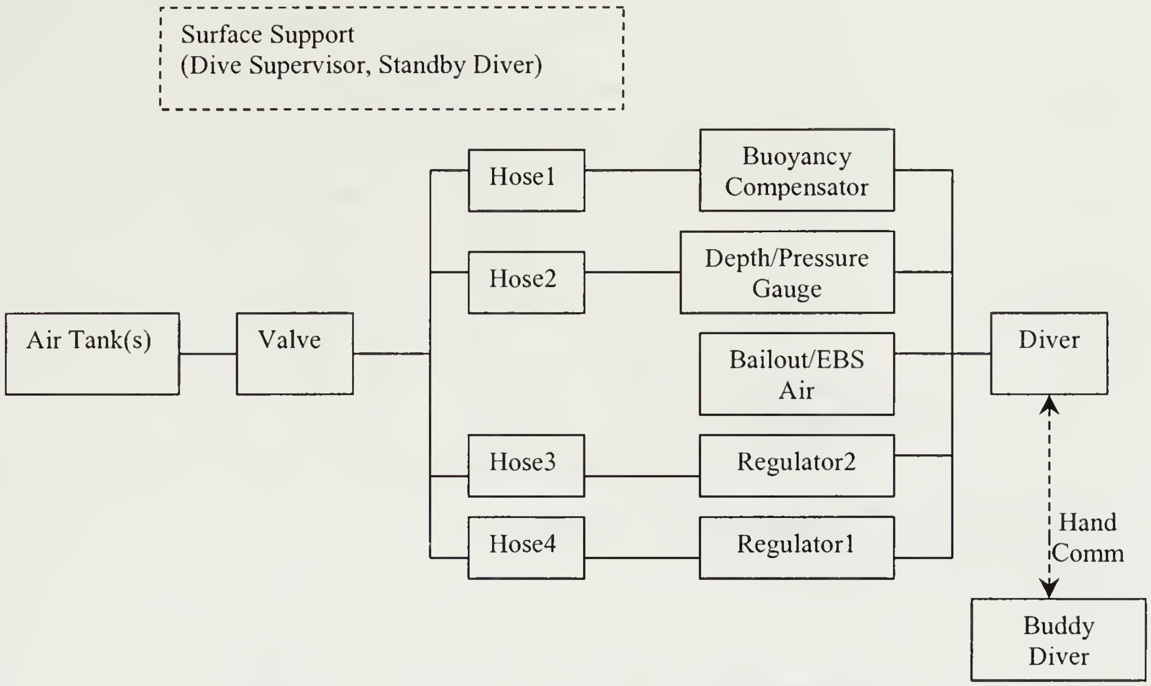


Figure 8: SCUBA System Diagram

4.2 Surface-Supplied Operations

The surface-supplied diving-system is widely used by commercial and military diving teams at depths up to 190 feet salt water (fsw). It offers significant advantages over SCUBA including increased air quantity, communications, and redundancy of air sources as shown in Figure 9. Areas of safety concern include 1) possibility of entanglement of umbilical, and 2) decompression concerns.

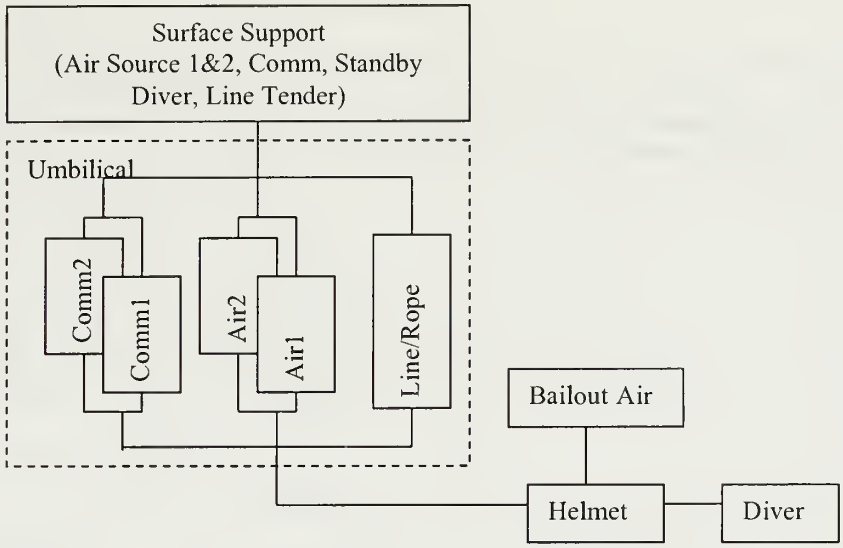


Figure 9: Surface-Supplied Diving System Diagram

4.3 Saturation Diving Operations

By far the most complex diving-system in use (see Figure 10), saturation diving offers the greatest depths and time on bottom (with the same decompression time once saturated). The operation basically consists of a deck decompression chamber (DDC) at the surface, a personnel transfer chamber (PTC) or bell for transit to and from project site, and either SCUBA or helmet dive systems from the PTC [Goodfellow, 1977]. Safety concerns are numerous for this type of system, but many feel it is safer than surface supply due to the crew redundancy, and component redundancies [Oman, 1994]. Some additional risks are associated with the use of pressure vessels (e.g. fires, explosions), and excursion diving (above and below) the PTC.

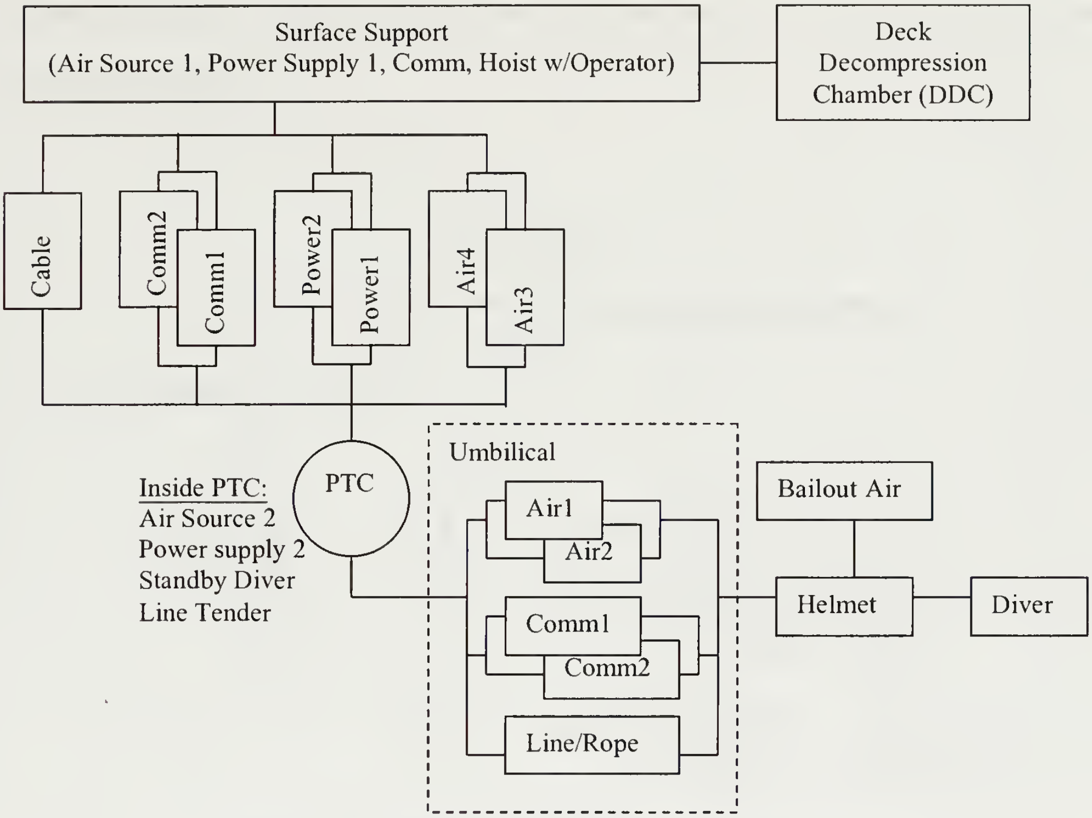


Figure 10: Saturation Diving System Diagram

4.4 Atmospheric Diving Systems (ADS)

The atmospheric diving systems (ADS) or one-man mobile submersibles are to date the most reliable systems in use [Rawlins and Hawkes, 1985]. This is primarily due to the fact that decompression sickness and arterial gas embolisms are not a concern. The most significant safety concerns with this type of diving system are as follows:

1) Hazards of high-pressure leaks at seals,

2) Entanglement or entrapment, and

3) Backup support in the case of an emergency.

The most important redundant system for ADS has proved to be the standby ADS diver as shown in Figure 11.

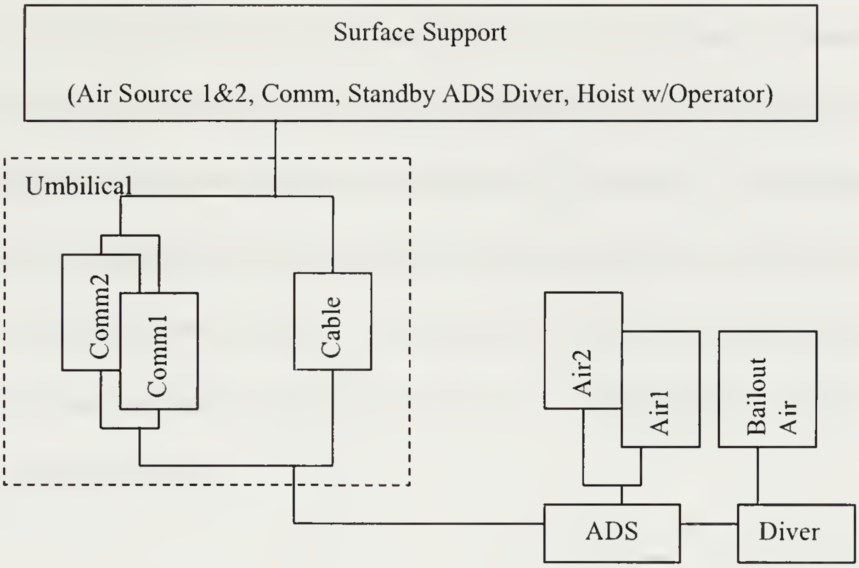


Figure 11: Atmospheric Diving System Diagram

5.0 Accident Data and Analysis

An accident is an undesirable event that may lead to loss of human life, personal injuries, significant damage to the environment or significant economic loss [Aven, 1992]. A near miss is an undesirable event without loss of life and personal injuries, and insignificant damage to the environment and insignificant economic loss, but which with small changes in the situation might have resulted in an accident. In diving operations, an accident can be further broken down into incident categories as shown in Figure 12 [Bea, 1998 and McSween, 1998]. This figure shows that for every diver fatality, there are 100 plus lost-time and recordable accidents, and 1,000 plus first aid cases, near mishaps, and unsafe acts.

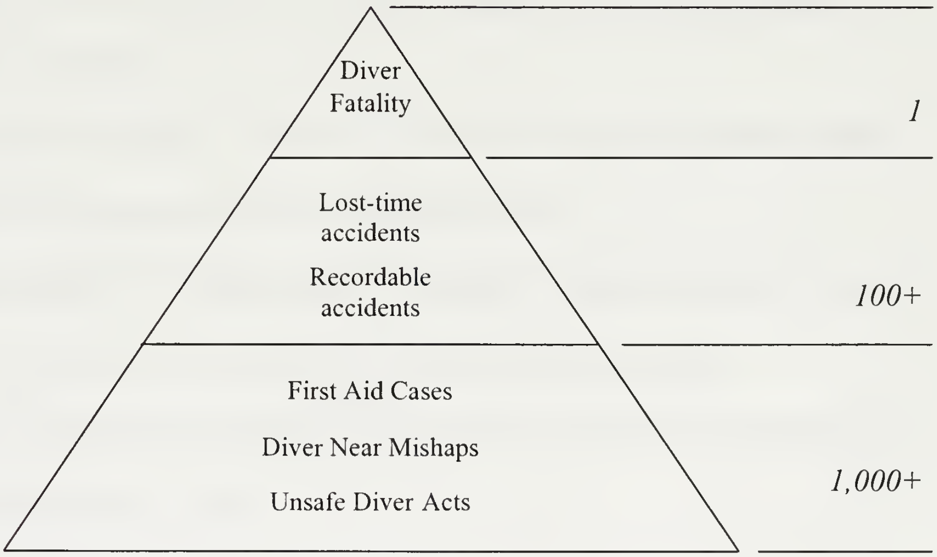


Figure 12: Accident Pyramid [adapted from Bea, 1998 and McSween, 1995]

The primary incidents and injuries resulting from diving operations are:

1) Type I decompression sickness (DCS-I) – which refers to skin "bends", fatigue or pain only (a result of breathing compressed gas).
2) Type II decompression sickness (DCS-II) – which includes neurological and cardio-respiratory "bend".
3) Arterial gas embolism (A.G.E.) – which represents arterialized gas bubbles primarily associated with immediate cerebral symptoms. A gas embolism occurs when a gas bubble causes a blockage of blood supply to the heart, brain, or other vital tissue.
4) Inert gas narcosis – a state of stupor or unconsciousness caused by breathing inert gas at pressure.
5) Asphyxia (or suffocation) and drowning – which occurs when the lung is unable to ventilate.
6) Barotrauma (or squeeze) – which occurs when some air-filled cavities of the body are not equalized to adjust to pressure change.
7) Carbon monoxide and carbon dioxide poisoning – which are a result of excess buildup occurs due to exertion and the lung is unable to ventilate.
8) Blowup – lung over-pressurization due to a rapid ascent without expelling air.

[NOAA Diving Manual, 1992]

5.1 DAN Diving Accident Data

Although the Diving Alert Network (DAN) is primarily concerned with recreational divers, their accident database provides valuable insight into the risk factors

and contributing causes of diving accidents. An evaluation of 270 accidents from 1987 revealed the common risk factors shown in Table 5 [Bennett, 1990]. Values in the right three columns indicate the number of times any two factors occurred together:

# of Cases	*Condition*	*Ascent*	*Fatigue*	*Current*
52 A.G.E. Cases Reported				
24	Rapid Ascent	-	9	8
18	Fatigue	9	-	8
16	Current	8	8	-
14	Buoyancy problem	11	4	3
11	Exertion on dive	7	4	7
47 Type I DCS Cases Reported				
22	Current	-	12	6
20	Exertion on dive	12	-	11
18	Fatigue	6	1	-
11	Cold	6	7	6
11	Alcohol	8	5	4
171 Type II DCS Cases Reported				
73	Current	-	28	37
64	Fatigue	28	-	31
58	Exertion on dive	37	31	-
42	Rapid ascent	17	18	20
31	Cold	17	18	22

Table 5: SCUBA Risk Factors

Dive day conditions and risk factors for Table 5 are listed in the following manner:

1) A strong to moderate current is considered a factor because of increased exertion.
2) Fatigue is a factor because the diver reported being physically tired or had missed some sleep the previous night.
3) Exertion is considered because of the increased muscle activity.
4) Cold is a factor because the diver said they were cold or uncomfortable.

Additional DAN fatality statistics for the 1980s [Bennett, 1990] show that major contributing factors were as follows: medical disorders (55.7%), environmental factors (34.8%), and equipment faults (9.5%). Other categories that were likely to contribute to the accident were inadequate air supply (56%), buoyancy problems (52%), and other equipment misuse (35%). The air supply (whether low on air or out of air) was a significant contributory factor as most problems occurred after the low on air situation. The buoyancy problems consisted of 48% negative buoyancy and 8% with positive buoyancy. Stress and fatigue were found to contribute to 39%, and 28% of the fatalities, respectively.

5.2 Naval Safety Center Diving Accident Data

From 1954-1996, there have been 79 fatalities and 4,673 incidents in U. S. military diving units [Naval Safety Center Data, 1996]. Figure 13 shows the breakdown of incidents by diving system used. Also of note, is the fact that 53% of the incidents were DCS and 30% were A.G.E. One significant deficiency with the database is the lack of total work-hours or number of dives conducted, and therefore there is no accurate way to determine incident rates.

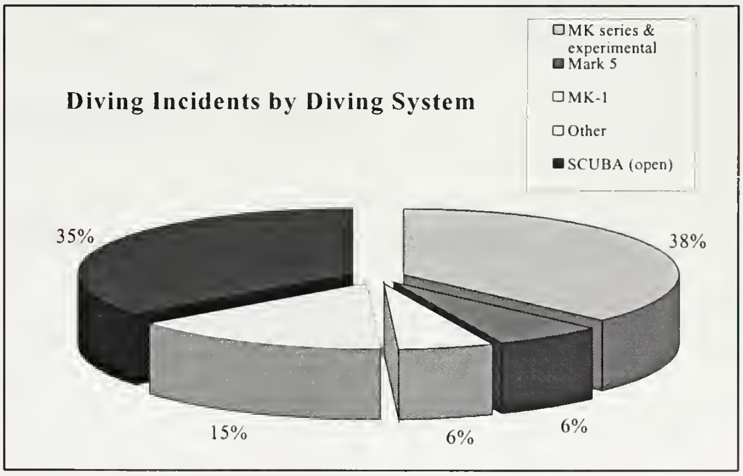


Figure 13: Diving Incidents by Diving System

5.3 Oceaneering Diving Incident Data

"Despite years of research and significant scientific advances, decompression sickness remains a problem and it is not totally preventable" [Youngblood, 1990]. Figure 14 shows overall incident rates for all dives performed by Oceaneering from the years 1983 through 1989. Of note, is the decreasing incident rate by 1989, which in terms of reliability analysis, the probability of failure is given by $P_f = 9.1 \times 10^{-4}$.

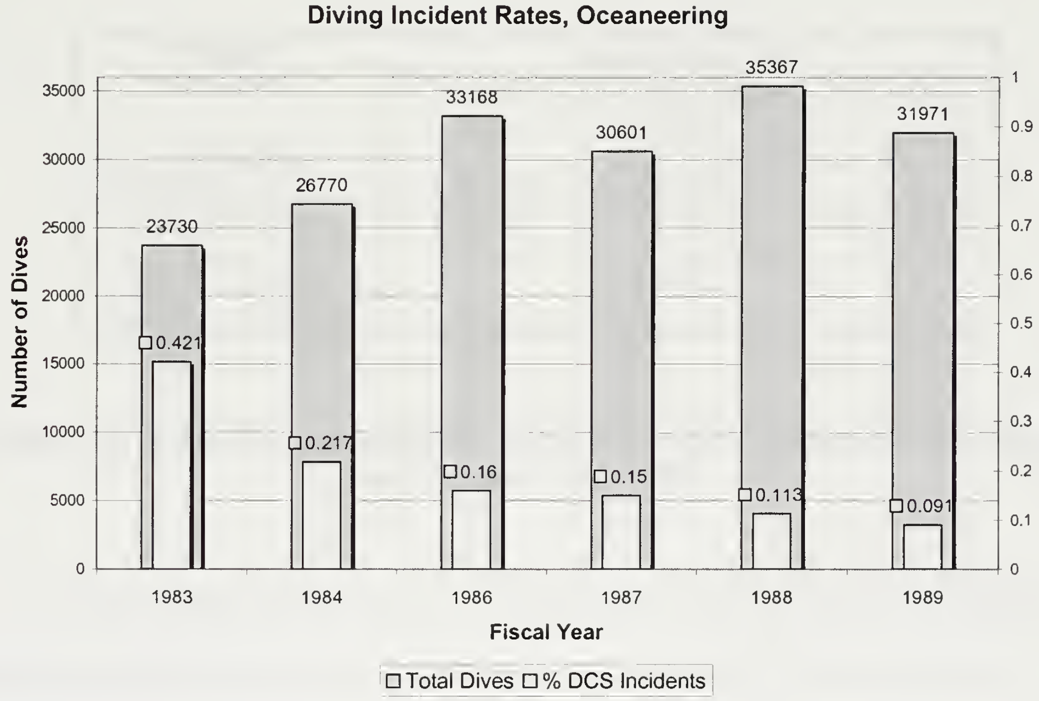


Figure 14: Diving Incident Rates, Oceaneering [from Youngblood, 1990]

5.4 North Sea Diving Incident Data

In a study of diver fatalities in the North Sea from 1971-1977, Table 6 was developed to quantify failure probability based on the number of fatalities. In this study, they found that 39% of the 39 deaths reviewed were caused by human factors and that a fraction of the other deaths could "probably be classified as human errors because of their dependence on human behavior" [Jacobsen and Stein, 1984].

FATALITY MEASURE	*Activity Exposure*		
	Surface-supply dive	Saturation (bell) Diving	Chamber stay
No. of fatalities	-	7	2
Fatalities per dive	1.80E-04	2.80E-04	-
Fatalities per hour activity	2.70E-04	3.00E-05	9.60E-07
Annual "individual fatality" rate estimate	3.90E-04		

Table 6: Diver Fatality Rate estimates on the Norwegian Continental Shelf [from Jacobsen and Stein, 1984]

In the United Kingdom's sector of the North Sea, a survey of all air commercial dives during 1982-1983, including 25,740 man dives, showed a total of 79 cases of decompression sickness, 44 Type I (0.17%) and 35 Type II (0.14%) [Bennett, 1990]. This would correspond to a $P_f = 1.7 \times 10^{-3}$ and $P_f = 1.4 \times 10^{-3}$, respectively for decompression sickness incidents.

5.5 OSHA Diving Statistics

The United States Department of Labor, Occupational Safety and Health Administration (OSHA), only monitors fatalities related to commercial diving. According to OSHA [1998], an average of 6 to 13 diving-related fatalities occur each year. With almost 10,000 workers employed as commercial divers, government divers, and sea harvesters, they face an exceptionally high risk of death and serious physical harm on the job, corresponding to 28 and 50 deaths per thousand workers over a working lifetime of 45 years.

6.0 HUMAN AND ORGANIZATIONAL FACTORS (HOF) IN DIVING

MacInnis [1972] was one of the earlier researchers to assess and evaluate the various HOF in diving accidents. Figure 15 was developed to show "The Diving Corridor of Effective Performance." MacInnis showed that performance underwater was primarily governed by the human factors, the water and gaseous environment, and the equipment and procedures.

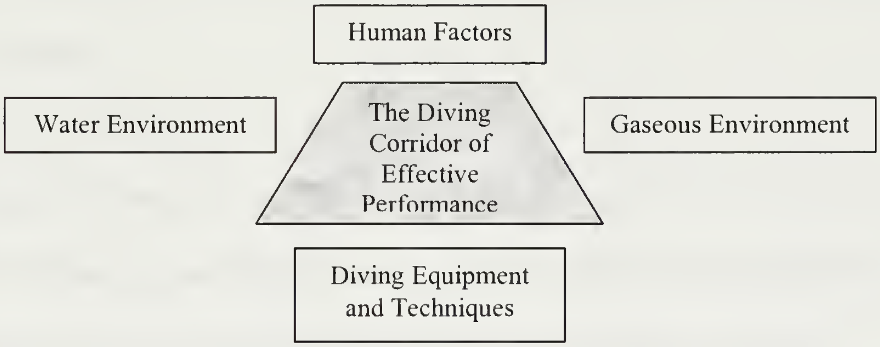

Human Factors
Water Environment
The Diving Corridor of Effective Performance
Gaseous Environment
Diving Equipment and Techniques

Figure 15: The Diving Corridor, Important Boundaries to Man's Effective Performance Within the Sea [from MacInnis, 1972]

In more recent years, Blumenberg [1996] and Cullen [1997] have provided insight into the fundamental HOF involved in SCUBA operations and underwater welding. Blumenberg [1996] specifically identified the following HOF influencing SCUBA diving operations and recommended the use of a Dive Team Human Factor Checklist to assess the role of HOF in the dive team:

1. Equipment (including tools, adaptation equipment, safety and protective, and life support).
2. Procedures (rules and regulations for each type of diving system employed).

3. Environment (pressure, cold, currents, limited visibility – all of which can change rapidly without warning).
4. Individual diver (dominant factor controlling safety is the diver's physical and mental fitness).
5. Organization (dominant controllable factor affecting the individual diver). The organization starts at the dive buddy team, includes the entire dive team, overall company or military unit, and the diving industry.
6. Interactions or interfaces between the preceding factors (most unpredictable factor).

Blumenberg [1996] noted two specific controllable areas which should receive the most focus; first, "improving individual awareness of human factors and the ability to cope with stress, and second, improving team coordination, reliability and culture."

In addition, Cullen [1997] recommended that a more in-depth qualitative and quantitative HOF assessment should be conducted to determine the role of HOF in diving incidents. In conducting this assessment, the assumption of positive correlation between failure modes was suggested to account for the fact that each failure would be the result of the mistakes of the same diver. The correlation would be a function of stress, physiological conditions, and the degree of training. It is the author's opinion that this assumption is correct and, to accurately assess the entire diving operation, correlation should be positive if the dive team has trained together sufficiently.

Based on this assumption, the probability of failure during a diving operation will be dominated by the maximum probability of failure. Therefore in most situations, the dominant term of Equation (2) will be the extrinsic human failure. It is this area which will be given the most focus, since the reliability of the overall system will only be improved through reduction of the human (diver) error.

6.1 Coarse Qualitative Analysis

Using a reactive risk management approach, taking into account the system safety concerns and past statistical data provided in sections 2.0 and 3.0, a coarse qualitative analysis can be performed for each diving system. Based on life-cycle evaluation of HOF in the diving system (Figure 6 shown earlier), failure to develop adequate safety will be the primary concern. In addition, since extrinsic causes have been related to 80% of marine accidents, and the operations phase results in the majority of accidents [Bea, 1998], the risk assessment will focus on the HOF in the diving operation. Cullen [1997] suggested that incidents could occur in each phase of the diving operation as shown in Figure 7 earlier.

The diving statistics indicate that decompression sickness (DCS) and arterial gas embolism (A.G.E.) are the greatest concerns and the result of most incidents. Both of these incidents would occur in the ascent and decompression phases of the diving operation. In addition, the statistics also indicate that the loss of air supply should also be

focused on, which again would usually occur during ascent and decompression or at the end of the bottom operation.

6.2 Detailed Qualitative Analysis

6.2.1 Failure Mode and Effect Analysis (FMEA)

A detailed qualitative analysis can now be performed for each diving system using the Failure Mode and Effect Analysis (FMEA) and the RAC prioritization method discussed earlier. Tables 7 through 10 represent FMEA for each system, respectively.

Identification of Component	Failure Mode	Hazard Severity	Loss Probability	Ranking (RAC)
Air Source	- Malfunction	I	D	3
	- Runs out due to Human error		B	1
Valve (1st Stage)	- Malfunction	III	D	5
	- O-ring failure		D	5
Hoses	- Entanglement	I	B	1
	- Cut or disconnect		D	3
Regulators	- Malfunction (purge)	III	B	3
	- Due to poor maintenance (human error)		A	2
Buoyancy Comp	- Malfunction	I	C	2
	- Accidental inflation (human error)		A	1
Depth/Press gauge	- Malfunction	II	D	4
Bailout/EBS	- Malfunction	II	D	4
	- Diver error in switching to it		B	2
Diver	- Mistakes	I	B	1
	- Selection & Training		C	2
	- Communication		A	1
	- Planning & preparation		B	1
	- Slips		C	2
	- Violations		D	3
	- Limitations & impairment		C	2
	- Ignorance		C	2
Dive Buddy	- Mistakes	I	B	1
	- Selection & Training		C	2
	- Communication		A	1
	- Planning & preparation		B	1
	- Slips		C	2
	- Violations		D	3
	- Limitations & impairment		C	2
	- Ignorance		C	2
Surface Support Organization	- Monitoring & Controlling	I	D	3
	- Culture		D	3
	- Communications		C	2
	- Mistakes		C	2

	- Planning & preparation		C	2
	- Structure & organization		B	1
	- Violations		D	3
	- Ignorance		C	2

Table 7: FMEA for SCUBA Diving System

Identification of Component	Failure Mode	Hazard Severity	Loss Probability	Ranking (RAC)
Air Source	- Malfunction	I	D	3
	- Runs out due to Human error		B	1
Helmet	- Malfunction (purge)	III	B	3
	- Due to poor maintenance (human error)		A	2
Communications	- Malfunction	III	C	4
Line/Rope (strength)	- Entanglement	II	C	3
	- Cut		D	4
Bailout Air	- Malfunction	II	D	4
	- Diver error in switching to it		B	2
Diver	- Mistakes	I	B	1
	- Selection & Training		C	2
	- Communication		A	1
	- Planning & preparation		B	1
	- Slips		C	2
	- Violations		D	3
	- Limitations & impairment		C	2
	- Ignorance		C	2
Line Tender, Standby Diver	- Mistakes	I	B	1
	- Selection & Training		C	2
	- Communication		A	1
	- Planning & preparation		B	1
	- Slips		C	2
	- Violations		D	3
	- Limitations & impairment		C	2
	- Ignorance		C	2
Surface Support Organization	- Monitoring & Controlling	I	D	3
	- Culture		D	3
	- Communications		C	2
	- Mistakes		C	2
	- Planning & preparation		C	2
	- Structure & organization		B	1
	- Violations		D	3
	- Ignorance		C	2

Table 8: FMEA for Surface-Supplied Diving System

Identification of Component	Failure Mode	Hazard Severity	Loss Probability	Ranking (RAC)
Air Source	- Malfunction	I	D	3
	- Runs out due to Human error		B	1
Helmet	- Malfunction (purge)	III	B	3
	- Due to poor maintenance (human error)		A	2
Communications	- Malfunction	III	C	4
Cable and Hoist	- Malfunction	I	D	3
	- Ship collision		D	3
Line/Rope (strength)	- Entanglement	II	C	3
	- Cut		D	4
PTC & DDC	- Fire onboard	I	D	3
	- Loss of pressure		D	3
	- Loss of power		D	3
Bailout Air	- Malfunction	II	D	4
	- Diver error in switching to it		B	2
Diver	- Mistakes	I	B	1
	- Selection & Training		C	2
	- Communication		A	1
	- Planning & preparation		B	1
	- Slips		C	2
	- Violations		D	3
	- Limitations & impairment		C	2
	- Ignorance		C	2
Line Tender, Standby Diver	- Mistakes	I	B	1
	- Selection & Training		C	2
	- Communication		A	1
	- Planning & preparation		B	1
	- Slips		C	2
	- Violations		D	3
	- Limitations & impairment		C	2
	- Ignorance		C	2
Surface Support Organization	- Monitoring & Controlling	I	D	3
	- Culture		D	3
	- Communications		C	2
	- Mistakes		C	2
	- Planning & preparation		C	2
	- Structure & organization		B	I
	- Violations		D	3
	- Ignorance		C	2

Table 9: FMEA for Saturation Diving System

Identification of Component	Failure Mode	Hazard Severity	Loss Probability	Ranking (RAC)
Air Source	- Malfunction	I	D	3
	- Runs out due to Human error		B	1
A.D.S. Suit	- Malfunction (leak in joint)	I	C	2
	- Due to poor maintenance (human error)		C	2
	- Pressure collapse (exceed depth limit)		D	3
Communications	- Malfunction	III	C	4
Cable and Hoist	- Entanglement	II	C	3
	- Ship collision		D	4
Bailout Air	- Malfunction	II	D	4
	- Diver error in switching to it		B	2
Diver	- Mistakes	I	B	1
	- Selection & Training		C	2
	- Communication		A	1
	- Planning & preparation		B	1
	- Slips		C	2

	- Violations		D	3
	- Limitations & impairment		C	2
	- Ignorance		C	2
Line Tender, Standby Diver	- Mistakes	I	B	1
	- Selection & Training		C	2
	- Communication		A	1
	- Planning & preparation		B	1
	- Slips		C	2
	- Violations		D	3
	- Limitations & impairment		C	2
	- Ignorance		C	2
Surface Support Organization	- Monitoring & Controlling	I	D	3
	- Culture		D	3
	- Communications		C	2
	- Mistakes		C	2
	- Planning & preparation		C	2
	- Structure & organization		B	1
	- Violations		D	3
	- Ignorance		C	2

Table 10: FMEA for Atmospheric Diving System

From these FMEA's performed for each diving system, a quantitative analysis can be conducted for the critical failure modes (e.g. failure modes with a RAC of 1, 2, or 3). In almost every system, the failure modes with a RAC of 1-3 correspond to HOF and loss of air source. Other failures as a result of lack of maintenance, ship collision, fire, or exceeding pressure depth limit can also be traced back to human or organizational error.

6.3 Quantitative Analysis

6.3.1 Coarse Quantitative Analysis

A complete and comprehensive quantitative analysis would require evaluation of all critical failure modes in each diving system. This in-depth analysis is beyond the scope of this paper, but by looking at the most common failure modes (loss of air and

decompression sickness) occurring in the ascent and decompression phase of the operation, a coarse quantitative evaluation can be performed integrating HOF.

Without remote operated vehicles (ROVs) or at-depth monitoring, the QA/QC will be relatively low and rely on the dive buddy or standby diver. For this reason, probability of detection is estimated at 0.25 and the probability of correction is estimated at 0.5. In addition, *performance shaping factor* multipliers (from Table 3) of 11 (for shortage of time) will be applied to the SCUBA system, and 1.3 (for stress) will be applied to all estimated generic human error rates (from Figure 4). Since decompression sickness is not a concern for ADS, no quantitative analysis will be performed.

Figures 16 through 18 on the following pages show the fault-trees using the HOF analysis methods discussed.

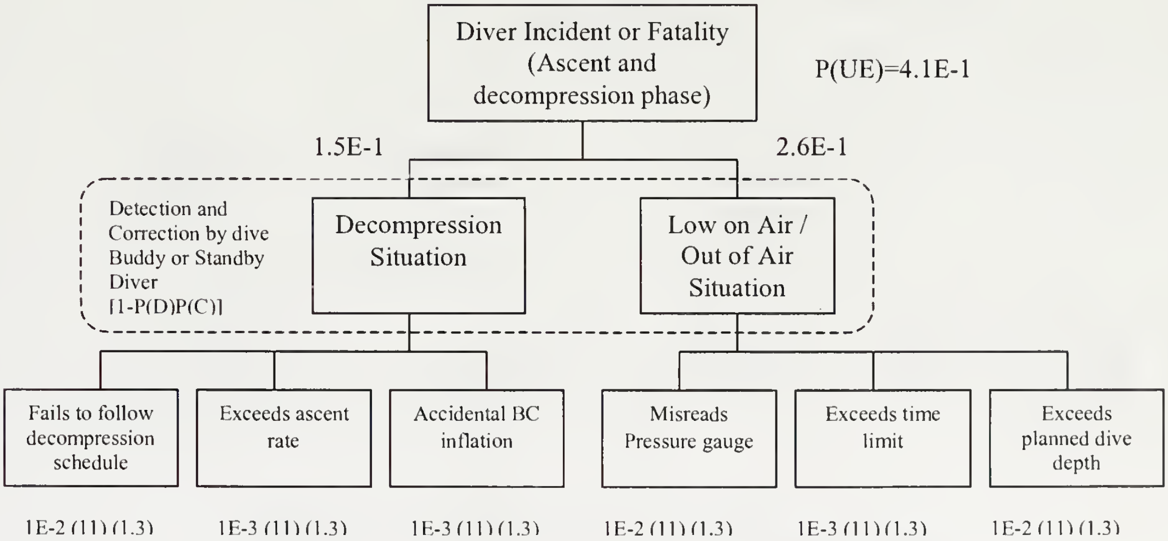

Diver Incident or Fatality (Ascent and decompression phase)
P(UE)=4.1E-1
1.5E-1
2.6E-1
Detection and Correction by dive Buddy or Standby Diver [1-P(D)P(C)]
Decompression Situation
Low on Air / Out of Air Situation
Fails to follow decompression schedule
Exceeds ascent rate
Accidental BC inflation
Misreads Pressure gauge
Exceeds time limit
Exceeds planned dive depth
1E-2 (11) (1.3)
1E-3 (11) (1.3)
1E-3 (11) (1.3)
1E-2 (11) (1.3)
1E-3 (11) (1.3)
1E-2 (11) (1.3)

Figure 16: SCUBA (Ascent and Decompression)

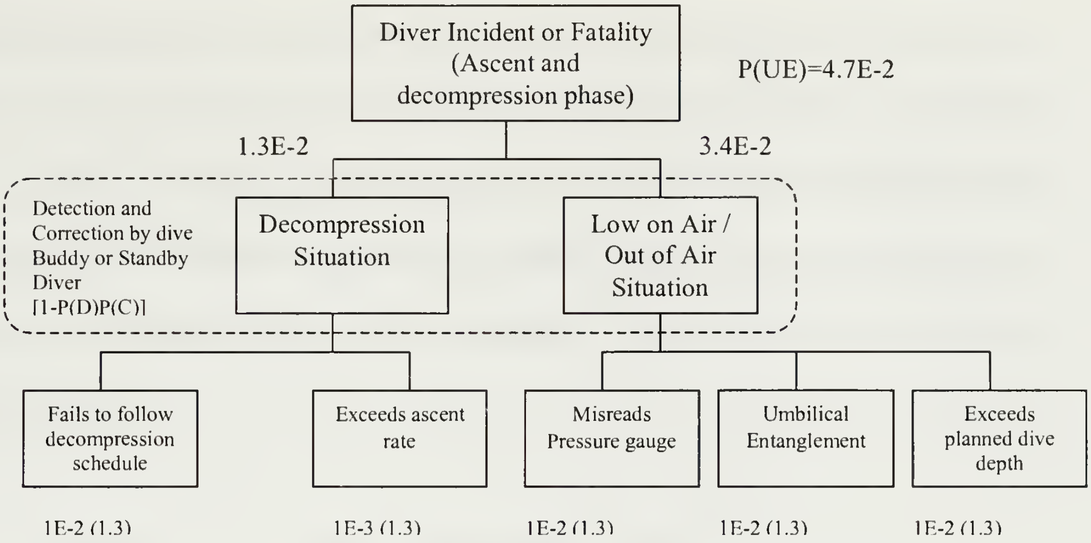

Diver Incident or Fatality (Ascent and decompression phase)
P(UE)=4.7E-2
1.3E-2
3.4E-2
Detection and Correction by dive Buddy or Standby Diver [1-P(D)P(C)]
Decompression Situation
Low on Air / Out of Air Situation
Fails to follow decompression schedule
Exceeds ascent rate
Misreads Pressure gauge
Umbilical Entanglement
Exceeds planned dive depth
1E-2 (1.3)
1E-3 (1.3)
1E-2 (1.3)
1E-2 (1.3)
1E-2 (1.3)

Figure 17: Surface Supply (Ascent and Decompression)

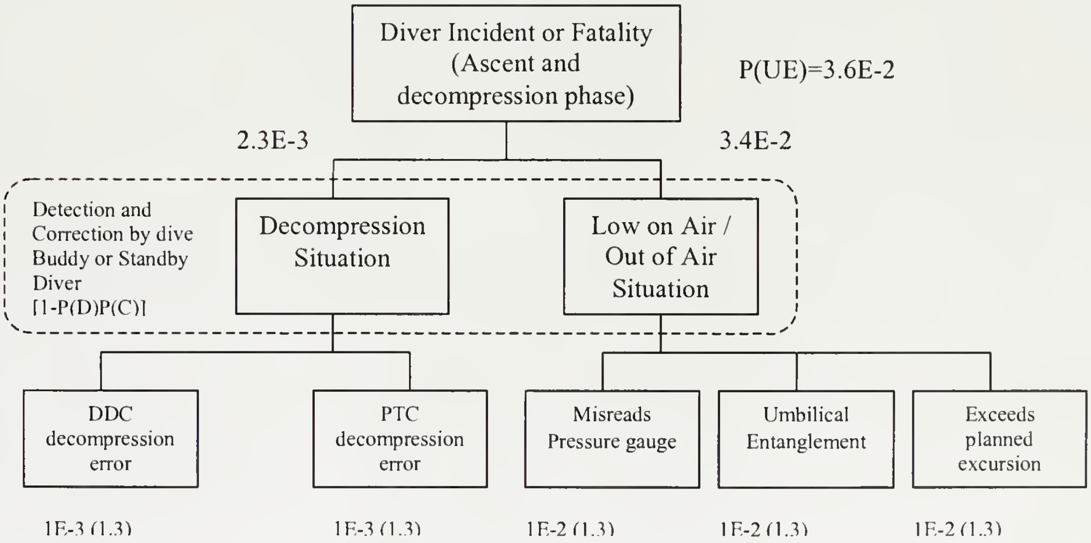


Figure 18: Saturation (Ascent and Decompression)

Applying Equations (2) through (4) as shown in Figures 16 through 18, the system probabilities can be approximated (based on the dominating extrinsic operation HOF evaluations and including the undetected and uncorrected QA/QC, [1 – (0.25)(0.5)] = 0.875). The summed human errors are multiplied by 0.875 to give the P(UE) and then multiplied by the probability of failure of the system conditional upon the human error (estimated at a likelihood of (B) 1E-2 in the FMEA). Total system failure probabilities are shown below.

1) SCUBA: $P(F_{Si}) = 1E\text{-}2\ (4.1E\text{-}1) = 4.1E\text{-}3$

2) Surface Supply: $P(F_{Si}) = 1E\text{-}2\ (4.7E\text{-}2) = 4.7E\text{-}4$

3) Saturation: $P(F_{Si}) = 1E\text{-}2\ (3.6E\text{-}2) = 3.6E\text{-}4$

7.0 SAFETY MANAGEMENT ASSESSMENT SYSTEM (SMAS)

Without accurate frequency of event's databases to estimate human error in the diving industry, a complimentary analysis involving a mixed qualitative and quantitative approach will be described. Significant research has been conducted in this field of assessment and management applicable to offshore installations and ships [Bea, 1997], [Hee, 1997], and [Pickrell, 1997]. This approach known as a Safety Management Assessment System (SMAS) should be applied to the diving operation.

A Safety Management Assessment System (SMAS) can be applied to the diving operation to enhance safety and minimize risk. The approach provides a systematic way of estimating the likelihood of events involving HOF and determining the risk (the product of the likelihood of failure and the consequences of that failure) [Bea, 1994].

7.1 Concept of SMAS

A Safety Management Assessment System (SMAS) is comprised of three components: 1) an auditing instrument, 2) an auditing process, and 3) an auditing team (composition, qualification, and training protocol) [Hee and Bea, 1997]. The primary focus of SMAS is on the HOF in a system, with emphasis given to the organization. SMAS is intended as a self-assessment and auditing device for those who are responsible for safety management.

The significance of SMAS, as opposed to other forms of human error checklists or evaluations, is that it incorporates the system operators [Pickrell, 1997]. Since the system operators are the most knowledgeable with regards to system safety issues, they can provide the most accurate and reliable human error database.

7.2 Likelihood Hierarchy

The evaluation process is organized into three levels as shown by Figure 19: 1) components and interfaces (or modules), 2) factors: detailed areas within the modules (the malfunction areas listed previously), and 3) attributes [Pickrell, 1997]. Grading scales with a range of 1 to 7, as previously shown, are used at the factors level. The assessors provide three grades: 1) most probable estimate, 2) lower bound, and 3) upper bound (creating a triangular distribution from which a mean can be derived for all assessors) [Hee and Bea, 1997].

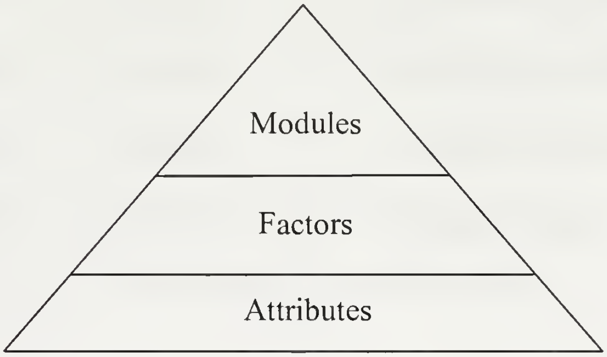


Figure 19: Likelihood Hierarchy

7.3 Consequence

For a diving operation, three types of consequences that should be addressed are as follows:

1) Cost (associated with equipment damage),
2) Lost work days, and
3) Injuries/fatalities.

The consequence scales applied to diving operations related to the above categories are listed in Table 11.

	Cost	Lost Work Days	Injuries/Fatalities
1	$0	0	0
2	$10	1 hour	First-aid only required/Near-mishaps
3	$100	12 hours	Reportable minor injury
4	$1,000	1 day	Multiple minor injuries
5	$10,000	10 days	Major injury/Lost Time Accidents
6	$100,000	100 days	1 fatality/Multiple major injuries
7	$1 million	1,000 days	Multiple fatalities

Table 11: Consequence Anchor Scales

7.4 Mathematical Concepts

To capture uncertainty, a "range" scoring method was proposed by Hee [1997] which requires the assessors to provide three scores for each attribute evaluated. The scores represent the best, most probable, and worst likelihood or consequence for each attribute being evaluated [Pickrell, 1997]. Using this concept, the "most probable" score captures the central tendency of the attribute while the "best" and "worst" scores show the uncertainty associated with that attribute.

Mathematically, the qualitative scores are translated into quantitative probabilistic distributions to determine the relative risk of failure. The scores are assumed to represent a unit triangular distribution with an area equal to one. This concept is illustrated in Figure 20 where point A represents the "best" score, point B represents the "most probable", and point C represents the "worst".

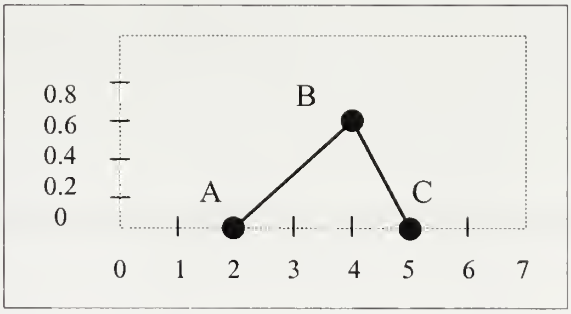


Figure 20: Sample Triangular Distribution

Using the triangular distribution discussed above, the mean and standard deviation can be derived using Algebra of Normal Functions as shown by Equations (6) and (7), respectively.

$$\overline{Z} = \frac{A+B+C}{3} \tag{6}$$

$$\sigma = \sqrt{\frac{(A^2 + B^2 + C^2 - AB - AC - BC)}{18}} \tag{7}$$

Continuing with the method of Algebra of Normal Functions, two triangular distributions can then be multiplied together. Given triangle 1 and triangle 2, their mean and standard deviation would be determined by Equations (8) and (9), respectively.

$$\overline{Z} = \overline{Z}_1 \times \overline{Z}_2 \tag{8}$$

$$\sigma = \sqrt{(\overline{Z}_1^{\,2} \cdot \sigma_2^{\,2} + \overline{Z}_2^{\,2} \cdot \sigma_1^{\,2} + \sigma_1^{\,2} \cdot \sigma_2^{\,2})} \tag{9}$$

Equations (6) through (9) form the basis for all computations required by SMAS.

7.5 A Diving Safety Management Assessment System (DSMAS)

7.5.1 DSMAS Process

The SMAS process as originally developed is based on three phases [Pickrell, 1997]. To modify the process for diving operations, a reactive step is added to phase 3. This step creates an incident/accident and near-mishap report process, which is fully integrated into the safety management system as shown in Figure 21. This phase will receive the primary focus and require full software implementation to supplement the current SMAS software developed by Pickrell [1997]. This was performed utilizing the Microsoft Access 97 software program.

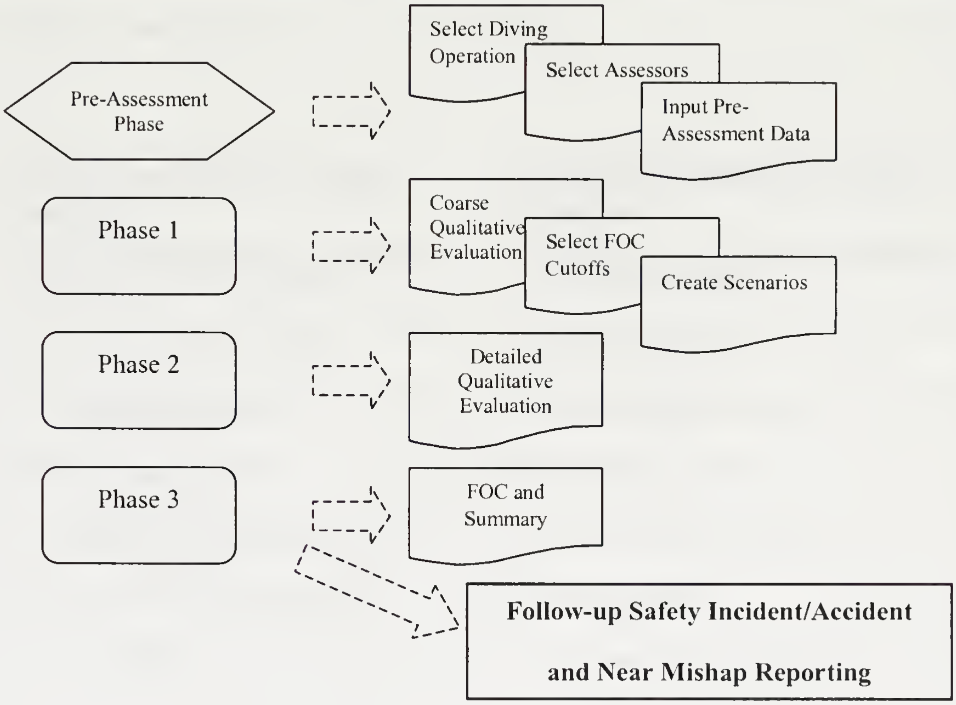

Pre-Assessment Phase
Select Diving Operation
Select Assessors
Input Pre-Assessment Data
Phase 1
Coarse Qualitative Evaluation
Select FOC Cutoffs
Create Scenarios
Phase 2
Detailed Qualitative Evaluation
Phase 3
FOC and Summary
Follow-up Safety Incident/Accident and Near Mishap Reporting

Figure 21: DSMAS Process Flow Chart [revised from Pickrell, 1997]

This fully integrated safety management system to assess HOF, a Diving SMAS, contains the following Diving Operation Modules:

1) Diving Team;
2) Diving Organization;
3) Dive Procedures/SOPs (standard operating procedures);
4) Structural (surface support platforms/pressure vessels);
5) Diving Equipment/systems;
6) Environmental;

Along with the consequence anchoring system discussed earlier, the coarse and detailed qualitative scoring of risk likelihood for the Diving SMAS factors is provided in Table 12 below [Hee, 1997].

Coarse Qualitative Scoring (General) (source: paperwork and interviews)	**Detailed Qualitative Scoring** (Specific) (source: site-visit and interviews)
1 = Best seen in diving industry	1 = Excellent condition
2 = Far exceeds requirements	2 = Good condition
3 = Exceeds requirements	3 = Adequate/good condition
4 = Meets requirements	4 = Adequate condition
5 = Almost meets requirements	5 = Adequate/poor condition
6 = Does not meet requirements	6 = Poor condition
7 = Not available	7 = Extremely poor condition

Table 12: Coarse and Detailed SMAS Scoring

7.5.2 DSMAS check-lists

Using the concepts of SMAS as discussed earlier, the author has adapted the assessment checklists for diving operations. In addition, based on the author's experience in Quality Control and Assurance for multi-million dollar construction projects, a 3-phase safety management assessment will be adopted which more closely follows a proactive quality control procedure.

7.5.3 Initial Diving Safety Assessment (Phase 1)

The initial diving safety assessment (phase 1) for the diving team module is provided in Appendix E. Similar assessment forms are included in the software to account for the diving organization, the dive standard operating procedures (SOPs), structural (surface support platforms/pressure vessels), diving equipment/systems, and environmental factors. This HOF assessment is primarily adapted from SMAS checklists [Pickrell, 1997] and the Dive Team Human Factors Checklist [Blumenberg, 1996]. Its main purpose is to obtain an initial assessment of HOF for the entire diving operation and identify factors of concern (FOC), which may warrant further evaluation (e.g. categories with means of 4 to 7).

7.5.4 Real-time Diving Safety Assessment (Phase 2)

The real-time diving safety assessment (phase 2) is similar to the initial, but conducted weekly (or as required) throughout the diving operation to provide continuous on-site assessment. Areas of concern would require immediate action and may warrant discontinuing the operation until mitigation or reduction measures are implemented. Appendix F shows the note-taking sheets for a detailed real-time assessment including all appropriate diving modules and attributes.

7.5.5 Follow-up Diving Safety Assessment (Phase 3)

The follow-up (phase 3) diving safety assessment contains fields to enter the key elements to the assessment, the near mishaps, lessons learned, and the incident reporting which addresses three categories of events and factors [Bea, 1996]:

1. Initiating events and factors that may have triggered the incident/accident sequence,
2. Propagating events and factors that may have allowed the incident/accident sequence to escalate and result in the accident, and
3. Contributing events and factors that may have encouraged the initiating and propagating events.

The information in the preceding categories would also address seven categories of factors:

1. Personnel (diving team) directly involved in the incident,
2. Organizations that may have had an influence on the events,
3. Procedures used at the time (formal and informal),
4. Diving Equipment and system used,
5. Structure (surface support platform, pressurized vessels/systems),
6. Environmental conditions, and
7. Interfaces between the preceding categories of factors.

And, would also address the life-cycle characteristics of history of the systems including, 1) design, 2) construction, 3) operation, and 4) maintenance.

Along with the reporting of total hours for the operation, and these key elements, accurate incident rates and a human error database (based on near-mishaps) can be developed, which can be used to further analyze the influence of HOF in diving operations. The phase 3 data-acquisition sheet is provided as Appendix G. This form is the basis of data entry and reporting that is fully integrated with the current SMAS software developed by Pickrell [1997].

The implementation of a fully integrated safety management system for diving operations made use of the recently developed SMAS software and included the phase 3

follow-up inspection forms and reporting. This type of safety management will provide an adequate method for assessing risk while providing a simple "user-friendly" system to track incidents/accidents and near-mishaps. Thus, it will provide a starting point for a diving HOF error database. In addition, commercial diving operators and military units will be able to obtain safety information to accurately generate the requisite safety reports for submission to OSHA and the Naval Safety Center, respectively.

8.0 CREW RESOURCE MANAGEMENT (CRM) AND TEAM TRANSITION

8.1 CRM Background

Crew resource management (CRM) is a method of training that was originally developed for the civilian aviation industry and later adapted and applied to military aviation, hospital emergency rooms, nuclear power plants, and even corporate management. In its simplest context, CRM is a tool that promotes team reliability through development of interpersonal skills. Although CRM has received mixed acceptance over the past two decades, the majority of pilots have endorsed it [Helmreich, Merritt, and Wilhelm, 1998].

The basic precepts of CRM are to enhance the overall performance of a man-machine operation by reducing the frequency and mitigating the consequences of human errors [Helmreich, and Merritt, 1996]. With this in mind, Helmreich and Merrit [1996] developed a layered pyramid (the "error troika"), which represents the 3 major goals of CRM as shown by Figure 22 on the following page.

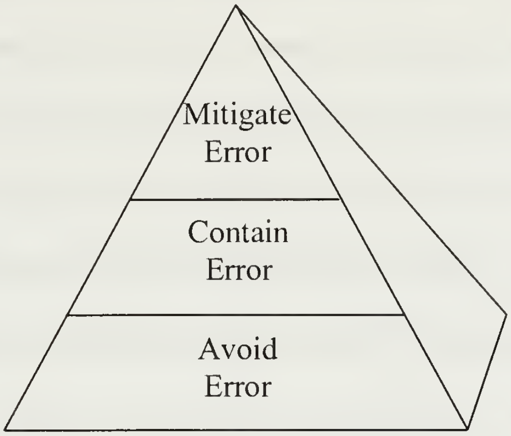


Figure 22: CRM "Error Troika" [Helmreich and Merritt, 1996]

Although CRM can not eliminate error and assure safety, it is one of an array of management tools that can be used to manage error [Helmreich, Merritt, and Wilhelm, 1998]. In their most recent research, Helmreich, Merritt, and Wilhelm [1998] have recommended an *error management* approach referred to as fifth generation CRM. Error management at the crew level is defined as:

> "Actions taken either to reduce the probability of errors occuring (error avoidance) or to deal with errors committed either by detecting and correcting them before they have operational impact (error containment/trapping) or to contain and reduce the severity of those that become consequential (error mitigation)" [Helmreich, and Merritt, 1998]

If error is inevitable, then CRM can be viewed as a method of countermeasures with the three lines of defense shown by the "error troika" pyramid.

With this approach of error acceptance, new initiatives have been announced by the Federal Aviation Administration, which actually encourage incident reporting and near-mishap reporting. This confidential and non-career jeopardizing approach has been successfully applied by American Airlines who have received nearly six thousand reports in a two-year period [Helmreich, Merritt, and Wilhelm, 1998]. It is this type of proactive safety management and data collection, which will allow companies and organizations to take steps towards minimization and mitigation of recurring incidents.

Since incidents are rare and unique events, incident data can not completely reveal how the system fails, the human contribution to these failures, and how training interventions can alleviate and contain them. An alternative but similar approach to CRM, a "Two-layered Surveillance", has been recently proposed by Maurino [1998] to assist with this safety concern. The first level includes line/normal simulation audits: surveys and observations by properly trained assessors/observers utilizing validated tools. The second level includes monitoring of the normal processes (e.g. communicating, budgeting, financing, training, monitoring, and allocating resources).

Again, this approach requires a consensus that "human error is unavoidable but manageable". The diving organization must accept that the problem is not with error itself, but with the consequences [Maurino, 1998]. In this perspective, the diving organization must also avoid reprimand for errors while maintaining confidentiality, else lose valuable incident or near-mishap data that could provide insight into minimization of future risks.

8.2 Team Transition Background

A final concept to enhance safety during diving operations is *team transition* training. Team transition refers to a situation that occurs when a team operators are functioning together for a period of time under routine conditions and then abruptly confronted abnormal and sometimes emergency circumstances [Huey, and Wickens, 1993]. Although this concept was originally applied to army tank crews, it is gaining acceptance by nuclear power plant operators, emergency medical service teams, and maritime ship operators.

During a diving operation, especially one involving mixed-gases and saturation diving systems, multiple crews may be used to perform a long-duration task. Not only do these crews deal with the transition arising from emergency procedures, but they also must face the transition from one crew to another. This is a critical time during the operation, which will require continual monitoring and assessment from the safety/dive supervisor.

The team transition study results most applicable to diving operations are summarized below:

1. "Adequate training and preparation, adapting strategies and tactics appropriate for the situation, effective leadership, and smooth crew coordination could

counteract some of the detrimental effects of imposed task demands" [Huey, and Wickens, 1993].

2. Better transition can be accomplished through preplanning, anticipating, and rehearsing actions to be taken under stress.
3. Special attention should be made to duty schedule, sleep periods, and comfort of systems being utilized.
4. Teams should maintain their integrity over a period of time. This concept is especially important to diving operations.
5. Crew composition and selection are vital.
6. While training, repetition and variety are essential.
7. Crisis management and decision-making must be practiced.
8. Problem solving must be trained first in a non-stressed environment first.
9. Fault diagnosis must be taught in complex systems (i.e. mixed-gas surface supplied and saturation diving systems).
10. Communication is paramount to the success of a mission.

8.3 Diving Risk Reduction through CRM and Team Transition

Risk reduction in diving operations can only be accomplished through a combination of proactive, real-time (or crisis management), and reactive safety management information systems and strategies. In each of these approaches, the most effective safety management can only be accomplished utilizing crew resource management (CRM) and transition team training as described above. In diving

operations, the crew (or dive team) is a crucial component to ensure safety. A dive team is usually 3 or more individuals and can be as large as 20 or more if considering saturation diving systems, which will include all hyperbaric and topside support personnel in addition to the divers. As such, the crew must be selected and effectively trained to handle all incident/accident scenarios that may occur.

This is not an easy task and involves extensive training and repetition of emergency procedures. Some measures for risk minimization and mitigation of diving operations using the concepts of CRM and transition team training are provided:

1. Improved competency and effective training of dive team personnel as a unit.
2. Maintenance of diving equipment program with team involvement.
3. Team evaluation of adequacy and effectiveness of diving procedures.
4. Team auditing and monitoring the Diving Safety Management System.
5. Increased reliability of the overall system by use of simulation or team training to model the actual operation or specific task to be performed (similar to NASA underwater training simulations for space repair projects).
6. Implementation of SMAS assessment forms as discussed.
7. Emergency preparedness and crisis management through repetitive simulator training and team involvement.
8. An acute awareness of the effects of team transition.

9.0 COMPUTER IMPLEMENTATION AND MONITORING

9.1 Computer Implementation of DSMAS

As stated earlier, implementation of a fully integrated safety management system for diving operations will make use of the recently developed SMAS software and include the phase 3 follow-up inspection forms and reporting. The current 1997 version of Microsoft's Access database-managed software will be the computer platform for this implementation phase. A database-structured approach is crucial to maintaining, tracking, and monitoring the influences and effects of HOF error on the overall operation.

The implementation involved four distinct steps:

1) Development of the data acquisition forms shown in Appendices E through H.
2) Development of a monthly summary safety report for each activity (Appendix I) and development of an input form/report for OSHA (Appendix J).
3) Revision of current data acquisition forms applicable to diving operations, and
4) Software testing utilizing the case study U.S. Navy fatality discussed earlier.

This type of safety management information system will provide an adequate and accurate method for assessing risk (before, during, and after a diving operation) while providing a simple "user-friendly" system to track incidents/accidents and near-mishaps. An organization will be able to use this system to monitor and manage safety proactively and review factors of concern on a monthly basis. A detailed analysis using PRA or

HRA techniques discussed earlier can then be developed for any areas or factors of concern. Steps can then be recommended to correct recurring HOF errors and minimize the overall risk to personnel.

9.2 Example Diving Accident

Although the DSMAS software is primarily to assess HOF before, during, and after a diving operation, a U.S. Navy dive accident which resulted in a fatality will be assessed and entered into the database to verify the accuracy of the software. A summary of the accident, which was also assessed by Blumenberg [1996], is provided and then entered into the DSMAS software.

9.2.1 Background of Accident

A U.S. Navy Seabee diver, assigned to Underwater Construction Team One, died on June 11, 1974 during a cable stabilization project in 100 feet of water. The direct cause of death was officially arterial gas embolism (A.G.E.) from a rapid ascent accompanied by breath holding, however, Blumenberg [1996] identified contributing and compounding factors that may have elevated the situation. These factors will be further sub-divided into initiating, propagating, and, compounding events to facilitate easy entry into the DSMAS software database.

9.2.2 Initiating Events and Factors

Diver did not end dive and return to surface before tank pressure reached 500 psi (formal procedure violated). Both divers failed to abort dive when pressure gages indicated empty tank. Diver showed evidence of panic during ascent when he grabbed buddies regulator. Entanglement may have caused panic and the uncontrolled rapid ascent.

9.2.3 Propagating Events and Factors

Dive team felt pressure to complete the work quickly because the support vessel was only available for a short time. Two inexperienced divers were paired as dive-buddies. Poor coordination of dive team put divers in water prior to having material resulting, which resulted in more air use. Initial dive brief was not clear to divers. Diver failed to monitor his air-supply. Buddy used inconsistent hand communications. Buddy failed to act early and recognize unsafe behavior of diver.

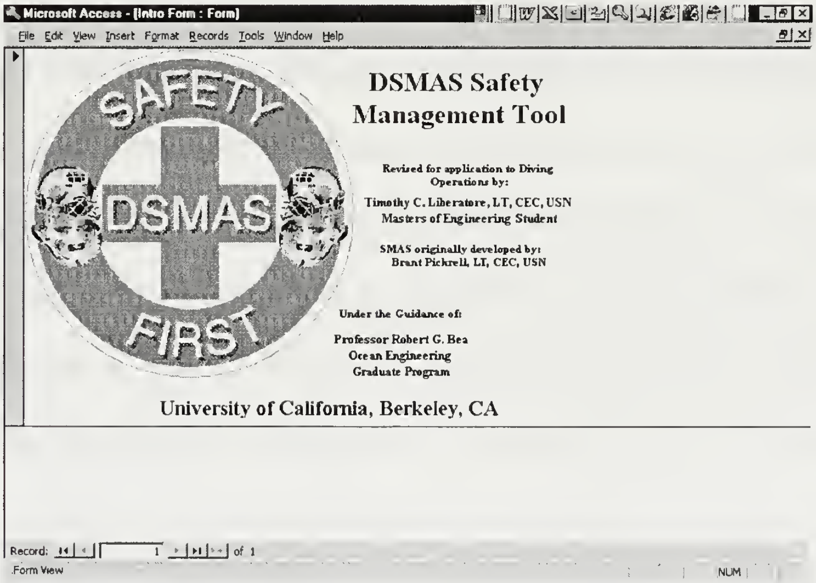
9.2.4 Contributing Events and Factors

The diver was a smoker. Diver was relatively new to the team and may have felt additional pressure from team members. Effects of nitrogen narcosis were unanticipated even though the diver had complained previous narcosis at similar depths. Diver had tendency to use air faster than most other divers did (plan assumed both divers would

work same maximum time). Initial training did not emphasize rescue skill and exhalation during buddy breathing. Diver was slightly seasick prior to dive. Work was physically demanding. Diver was using a borrowed regulator which had been adjusted to breath easier. Buddies did not communicate a change in the dive profile. Dive team culture condoned exceeding air limits.

9.3 Data Entry with DSMAS

By starting the DSMAS software enclosed (Appendix K), the screen shown in Figure 23 appears and then minimizes to show the DSMAS main menu (shown in Figure 24).


Microsoft Access - [Intro Form : Form]
File Edit View Insert Format Records Tools Window Help
SAFETY
DSMAS
FIRST
Record: 1 of 1
Form View
NUM

DSMAS Safety
Management Tool

Revised for application to Diving
Operations by:
Timothy C. Liberatore, LT, CEC, USN
Masters of Engineering Student

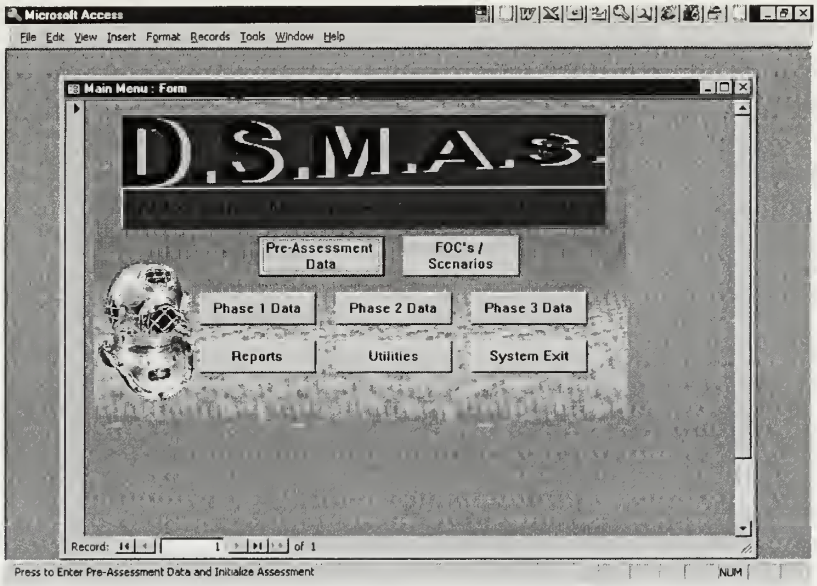
SMAS originally developed by:
Brant Pickrell, LT, CEC, USN

Under the Guidance of:

Professor Robert G. Bea
Ocean Engineering
Graduate Program

University of California, Berkeley, CA

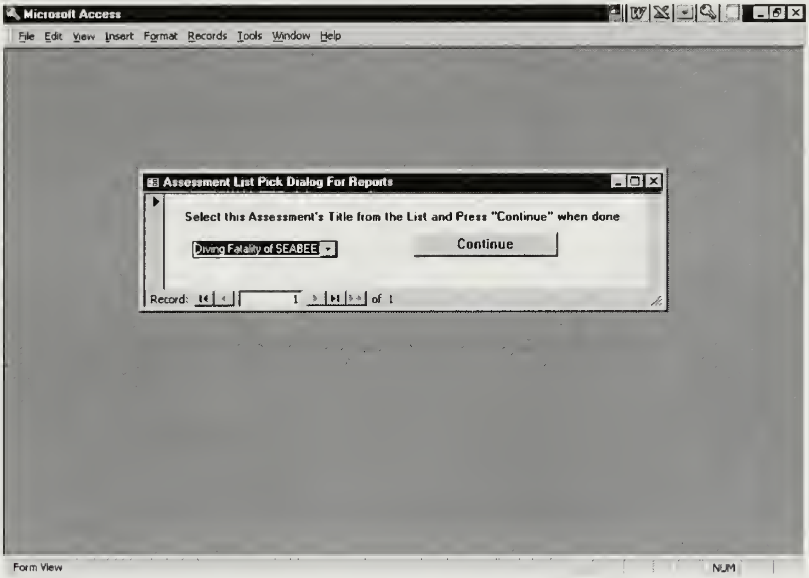
Figure 23: DSMAS Intro Screen



Press to Enter Pre-Assessment Data and Initialize Assessment

Figure 24: DSMAS Main Menu Screen

From the main menu screen (Figure 24), the initial assessment information is entered following the SMAS manual contained in Pickrell [1997] and Hee [1997]. The pre-assessment data is entered first, followed by the phase 1 and phase 2 data. The phase 1 data was entered for the U.S. Navy fatality discussed earlier and a summary report is included as Appendix F, which can be used to assess areas of concern. The data acquisition forms are included in the report section of the software. By pressing the Reports button, Figure 25 will appear prompting for selection of an assessment. If an assessment has been entered, it will appear on the pull-down menu (search by clicking the down arrow).

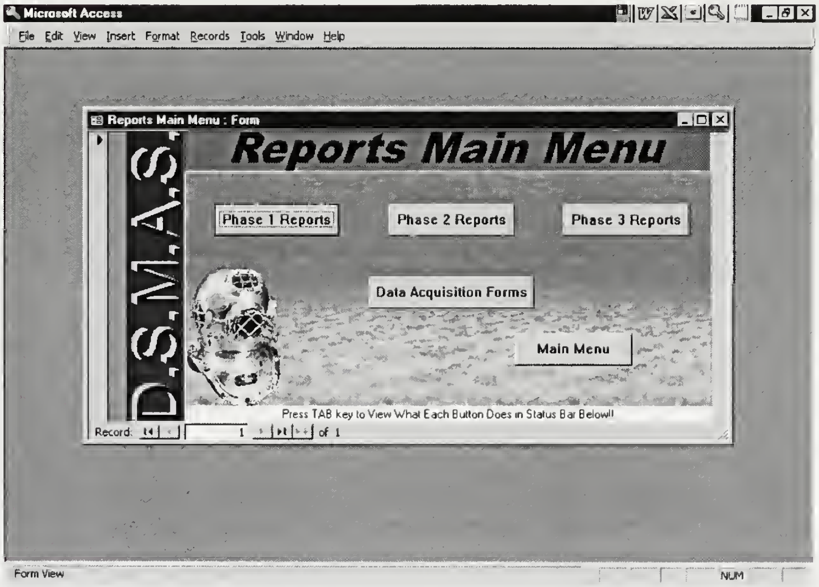

Microsoft Access
File Edit View Insert Format Records Tools Window Help
Assessment List Pick Dialog For Reports
Continue
Record: 1 of 1
Form View
NUM

Select this Assessment's Title from the List and Press "Continue" when done

Diving Fatality of SEABEE

Figure 25: Assessment Selection Screen

The reports main menu (Figure 26) will now appear. Select the Data Acquisition Forms button.



Press TAB key to View What Each Button Does in Status Bar Below!!

Figure 26: Reports Main Menu Screen

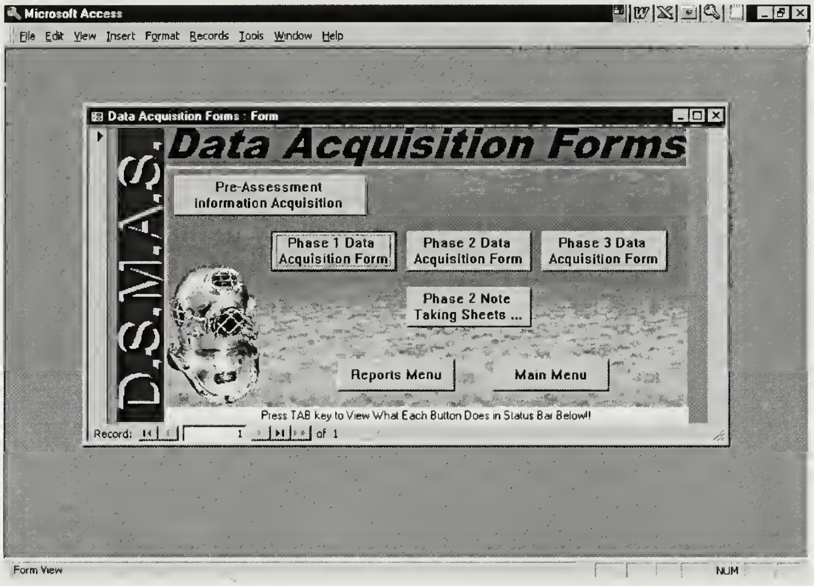
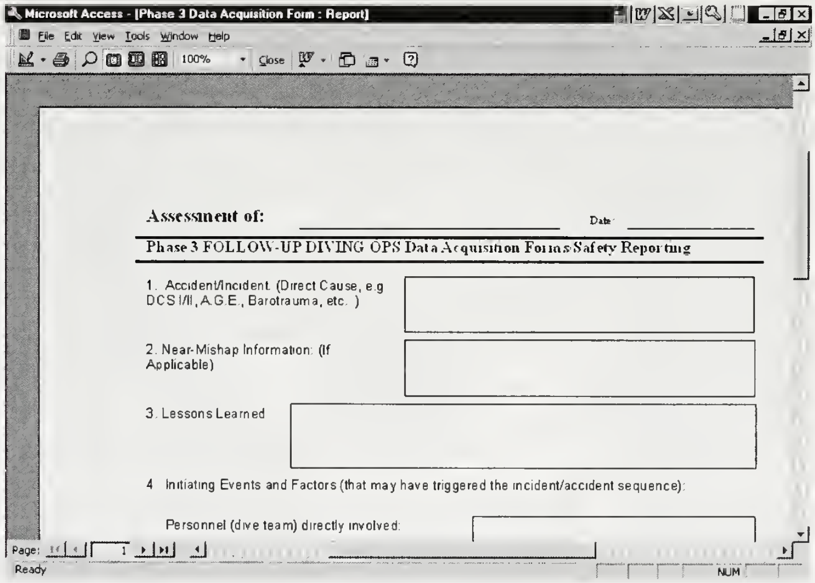

Microsoft Access
File Edit View Insert Format Records Tools Window Help
Data Acquisition Forms : Form
D.S.M.A.S.
Data Acquisition Forms
Pre-Assessment Information Acquisition
Phase 1 Data Acquisition Form
Phase 2 Data Acquisition Form
Phase 3 Data Acquisition Form
Phase 2 Note Taking Sheets ...
Reports Menu
Main Menu
Press TAB key to View What Each Button Does in Status Bar Below!!
Record: 1 of 1
Form View
NUM

Figure 27: Data Acquisition Screen

The data acquisition form appears (Figure 27). From this form, the user can select the phase 1, phase 2, or phase 3 data acquisitions forms. Select the Phase 3 form to switch to a print preview of the form (Figure 28). The user can then print the form.


Microsoft Access - [Phase 3 Data Acquisition Form : Report]
File Edit View Tools Window Help
100%
Close
Page: 1
Ready
NUM

Assessment of: ______________ Date: ______________

Phase 3 FOLLOW-UP DIVING OPS Data Acquisition Forms Safety Reporting

1. Accident/Incident. (Direct Cause, e.g DCS I/II, A.G.E., Barotrauma, etc.)

2. Near-Mishap Information: (If Applicable)

3. Lessons Learned

4 Initiating Events and Factors (that may have triggered the incident/accident sequence):

Personnel (dive team) directly involved:

Figure 28: Phase 3 Data Acquisition Form Screen

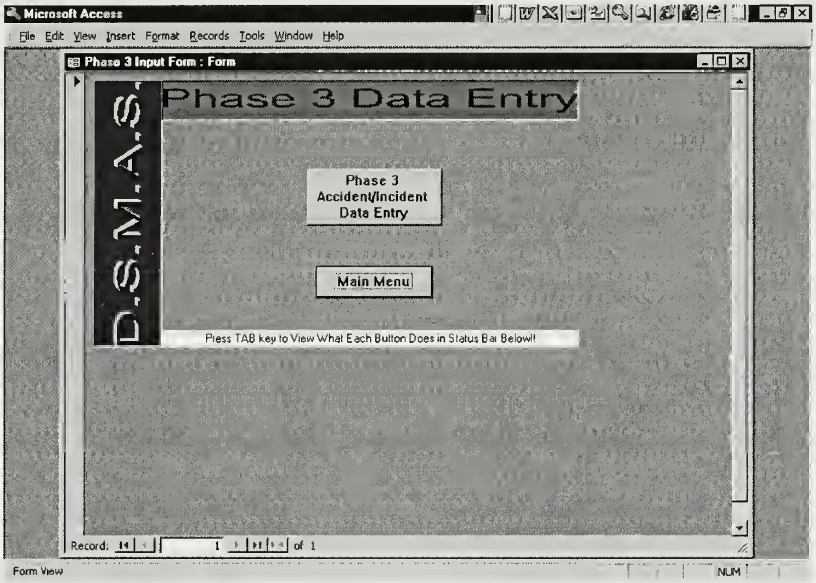
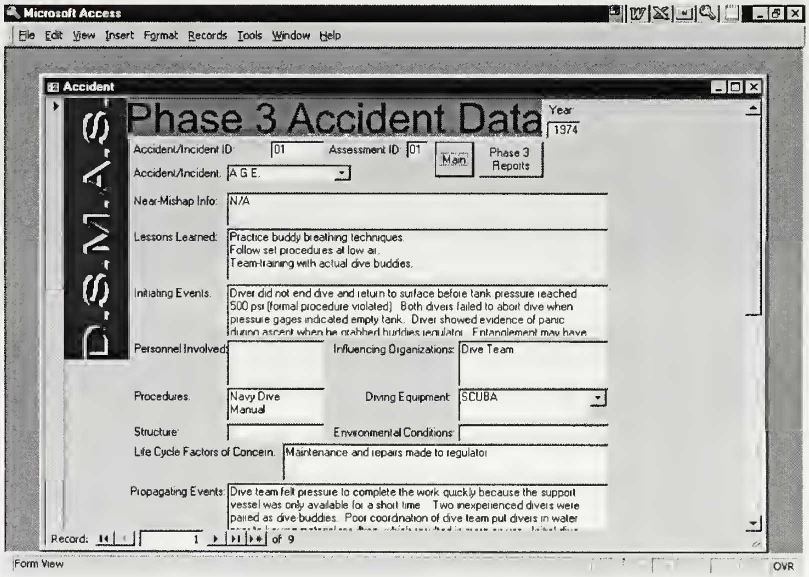

Microsoft Access
File Edit View Insert Format Records Tools Window Help
Phase 3 Input Form : Form
D.S.M.A.S.
Phase 3 Data Entry
Phase 3 Accident/Incident Data Entry
Main Menu
Press TAB key to View What Each Button Does in Status Bar Below!!
Record: 1 of 1
Form View
NUM

Figure 29: Phase 3 Data Entry Screen

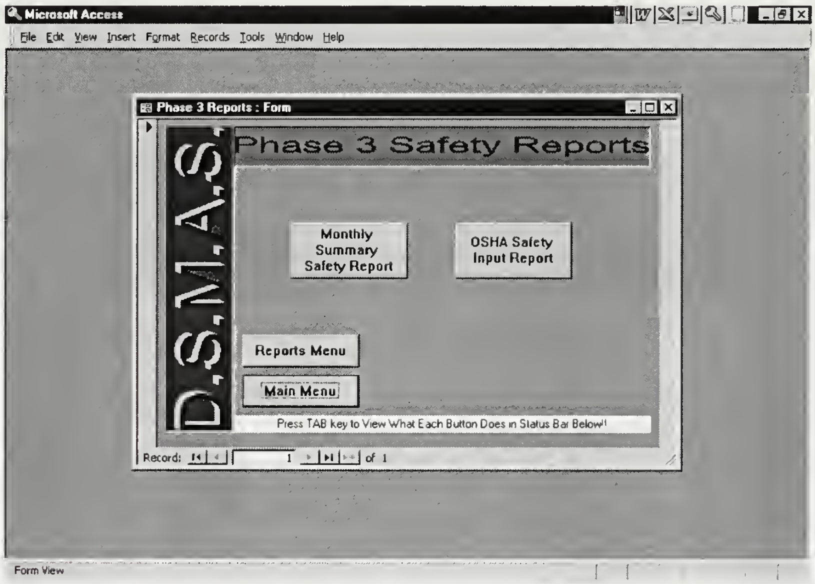
Close the phase 3 form and return to the main menu. Select Phase 3 data entry to perform the follow-up safety assessment. Figure 29 will appear. Select the Phase 3 Accident/incident Data Entry button to switch to the input screen (Figure 30).



Year: 1974
Accident/Incident ID: 01
Assessment ID: 01
Accident/Incident: A.G.E.
Near-Mishap Info: N/A
Lessons Learned: Practice buddy breathing techniques.
Follow set procedures at low air.
Team-training with actual dive buddies.
Initiating Events: Diver did not end dive and return to surface before tank pressure reached 500 psi (formal procedure violated). Both divers failed to abort dive when pressure gages indicated empty tank. Diver showed evidence of panic during ascent when he grabbed buddies regulator. Entanglement may have
Personnel Involved:
Influencing Organizations: Dive Team
Procedures: Navy Dive Manual
Diving Equipment: SCUBA
Structure:
Environmental Conditions:
Life Cycle Factors of Concern: Maintenance and repairs made to regulator
Propagating Events: Dive team felt pressure to complete the work quickly because the support vessel was only available for a short time. Two inexperienced divers were paired as dive-buddies. Poor coordination of dive team put divers in water

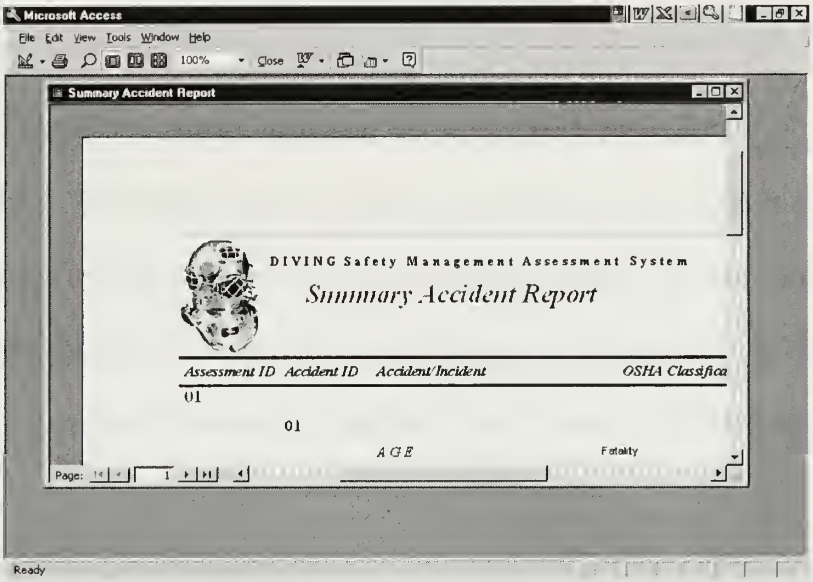
Figure 30: Accident Data Entry Screen

Assign an ID number for each accident or incident and enter all necessary data that was recorded earlier on the phase 3 data acquisition sheet. Multiple incidents can be entered for each assessed activity. Remember to scroll down to enter all information. Once all accident information is entered, the user can select the Main Menu button or the Phase 3 Reports Menu. By selecting the Phase 3 Reports Menu, Figure 31 will appear, where the user can immediately go to one of the safety reports. Figure 32 shows the Monthly Summary Safety Report and Figure 33 shows the OSHA Safety Input Report performed for the U.S. Navy fatality discussed earlier. Appendices I and J show the output results for that accident.



Press TAB key to View What Each Button Does in Status Bar Below!

Figure 31: Safety Reports Screen

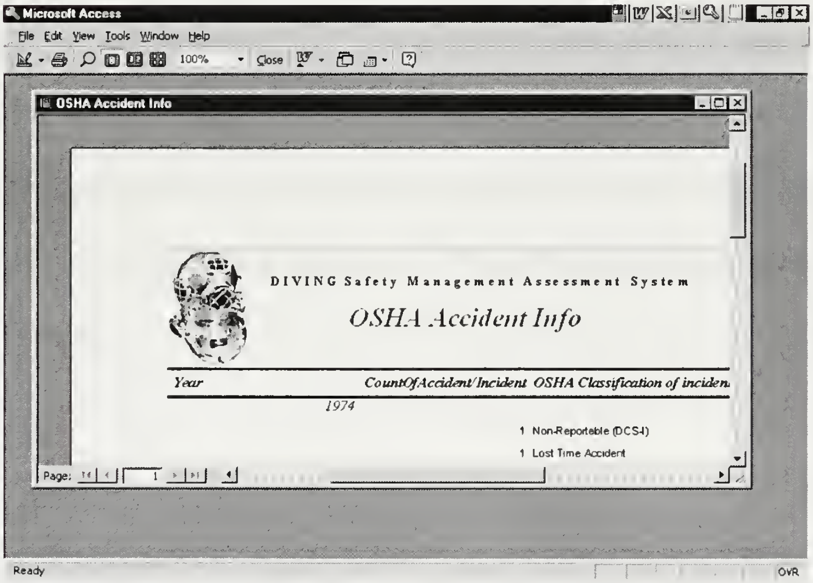


DIVING Safety Management Assessment System

Summary Accident Report

Assessment ID	Accident ID	Accident/Incident	OSHA Classifica
01			
	01		
		AGE	Fatality

Figure 32: Summary Accident Report Screen



DIVING Safety Management Assessment System

OSHA Accident Info

Year	CountOfAccident/Incident	OSHA Classification of inciden
1974		
	1	Non-Reportable (DCS-I)
	1	Lost Time Accident

Figure 33: OSHA Accident Info Screen

9.4 Monitoring of Diving Operations

The final question remaining is how can an organization effectively monitor a diving operation? With today's rapidly growing and diverse array of technological advancements, the answer may still be a man-machine interface. In this context, the combination of remotely operated vehicles (ROV) and on-site supervision may provide the most effective means of evaluating, assessing, and avoiding crisis situations.

As with any project, decision making should be empowered to the lowest level practicable. However due to the nature and high-risk of the underwater environment, any additional insight and monitoring from surface support platforms can only enhance the likelihood of success and minimization of HOF error. With this concept in mind, the diving organization must recognize that "human error is inevitable" [Maurino, 1998], yet understand that error can be minimized and managed to an acceptable level. This can be accomplished successfully just as it is currently being done in the aviation community with the proactive use of the fifth generation CRM and the safety assessment tools provided in this paper.

10.0 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, with the continued need for manned-diving operations in the offshore oil industry and the military, there will continue to be extrinsic risks placed on divers. This paper has attempted to apply complimentary approaches of Safety Management and Assessment Systems (SMAS), incident/accident reporting criteria, and Crew Resource Management (CRM) to develop management tools that assess human and organizational factors (HOF) in diving operations. In addition, the follow-up assessment (phase 3) of the diving safety management system was outlined and implemented in detail, which fully integrates assessment and monitoring of diving operations with incident/accident reporting legislature.

Through this proactive type of safety management, diving organizations can begin to create a HOF database that will assist in continued risk analysis and minimization of manned-diving operations. The database can be used to categorize incidents/accidents and near-mishaps, and assist with evaluating factors of concern. The sample diving fatality was successfully entered into the software database (DSMAS) and shows that an integrated safety management system can be developed and modified to assist an organization with risk assessment, management, and reporting.

Recommendations for continued research dedicated to risk minimization of diving operations are given below:

1. Field verification and modification of the enclosed forms and reports (generated by the DSMAS software) to meet the missions of the organizations.
2. Real-time testing of the DSMAS software by military and commercial diving organizations.
3. Continued efforts to promote safety of manned-diving operations through proactive Diving Safety Management Systems that are monitored and used for initial planning, real-time evaluation, and follow-up reporting.
4. Evaluation of risk reduction and minimization of human factors through alternative underwater systems such as remotely operated vehicles (ROV) and atmospheric diving systems (ADS).

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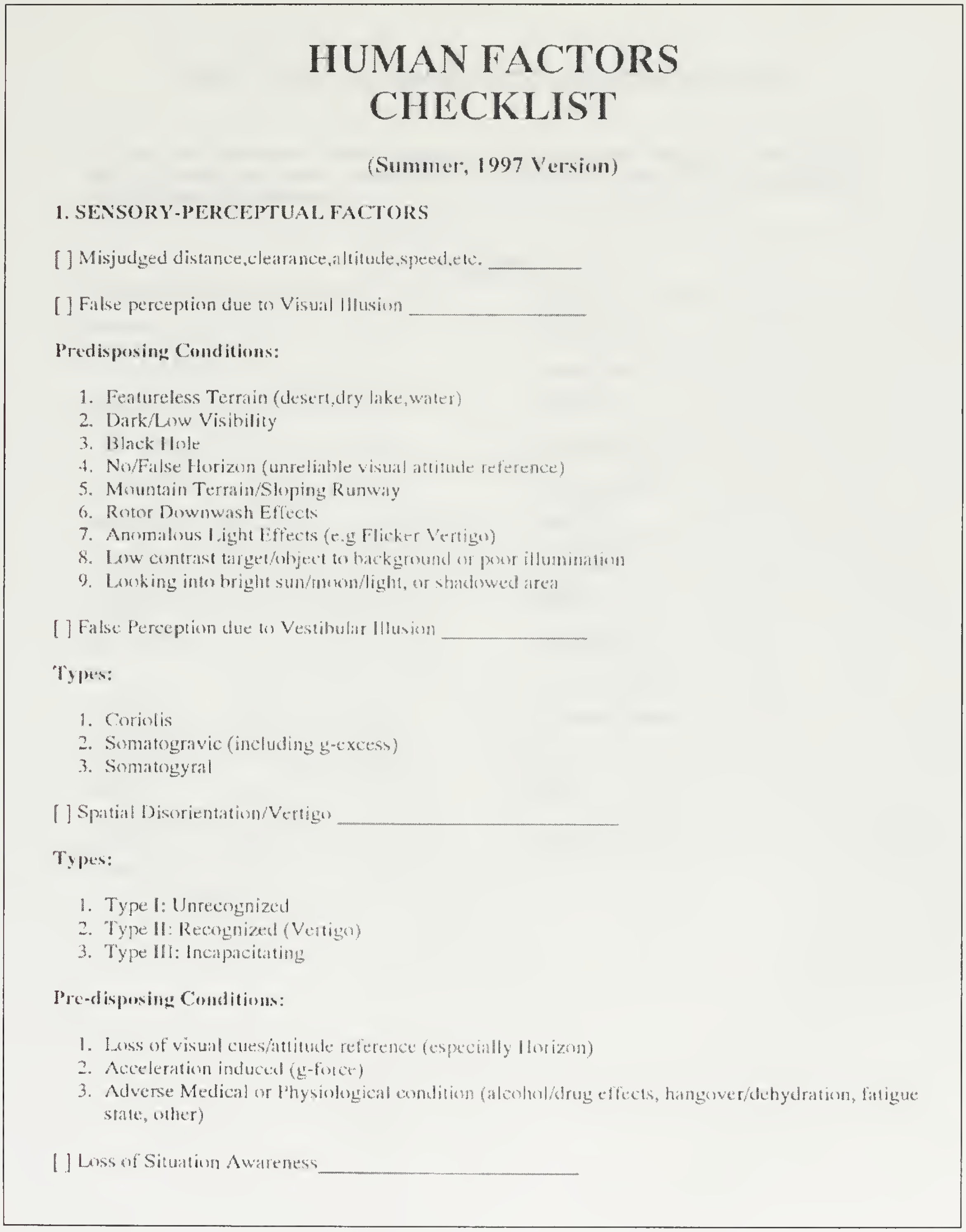
APPENDICES

APPENDIX A: Aviation HOF Checklist



HUMAN FACTORS CHECKLIST

(Summer, 1997 Version)

1. SENSORY-PERCEPTUAL FACTORS

[ ] Misjudged distance,clearance,altitude,speed,etc. __________

[ ] False perception due to Visual Illusion __________________

Predisposing Conditions:

1. Featureless Terrain (desert,dry lake,water)
2. Dark/Low Visibility
3. Black Hole
4. No/False Horizon (unreliable visual attitude reference)
5. Mountain Terrain/Sloping Runway
6. Rotor Downwash Effects
7. Anomalous Light Effects (e.g Flicker Vertigo)
8. Low contrast target/object to background or poor illumination
9. Looking into bright sun/moon/light, or shadowed area

[ ] False Perception due to Vestibular Illusion ________________

Types:

1. Coriolis
2. Somatogravic (including g-excess)
3. Somatogyral

[ ] Spatial Disorientation/Vertigo ______________________________

Types:

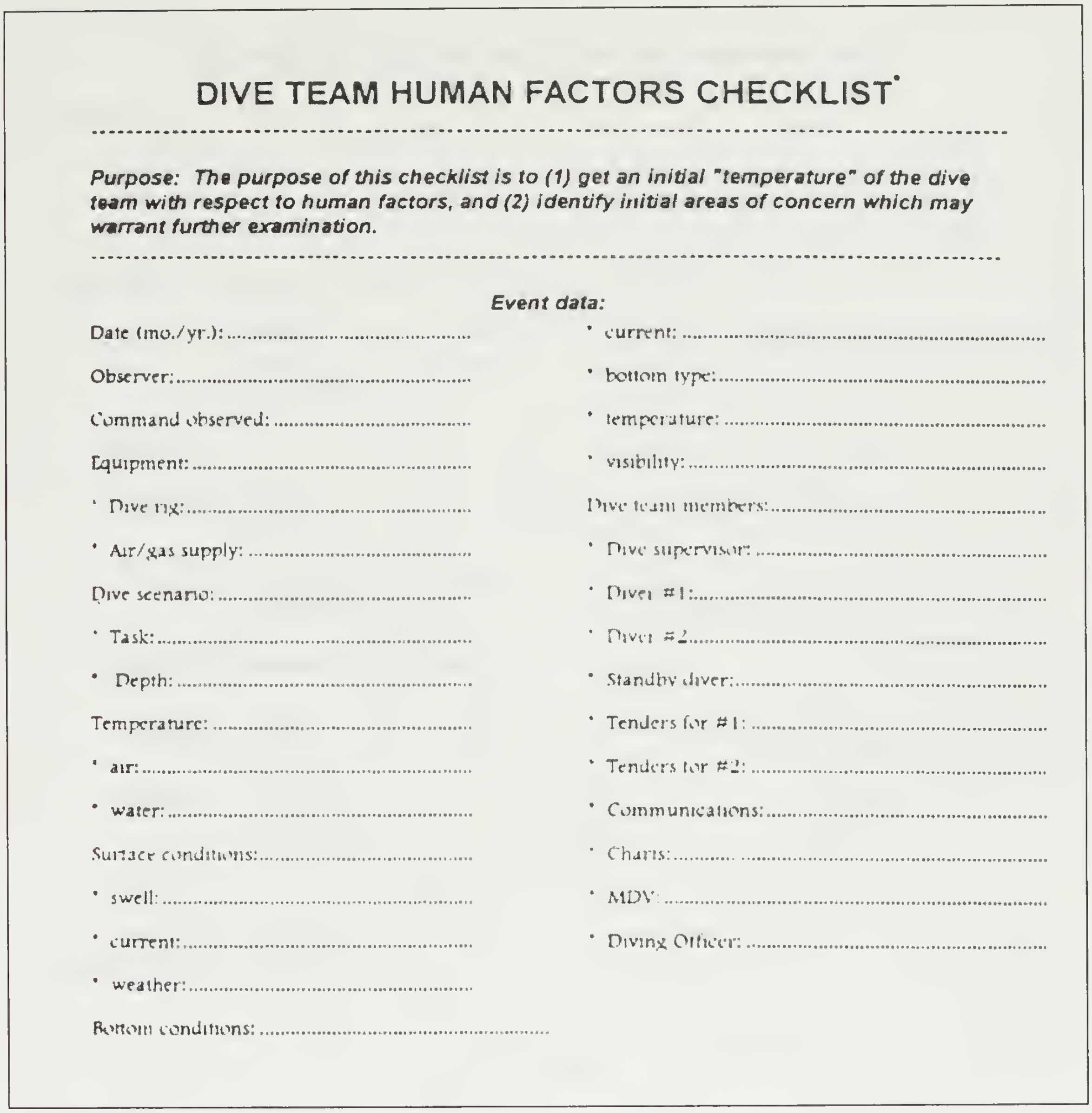
1. Type I: Unrecognized
2. Type II: Recognized (Vertigo)
3. Type III: Incapacitating

Pre-disposing Conditions:

1. Loss of visual cues/attitude reference (especially Horizon)
2. Acceleration induced (g-force)
3. Adverse Medical or Physiological condition (alcohol/drug effects, hangover/dehydration, fatigue state, other)

[ ] Loss of Situation Awareness____________________________

APPENDIX B: Diving HOF Checklist



DIVE TEAM HUMAN FACTORS CHECKLIST*

***Purpose:** The purpose of this checklist is to (1) get an initial "temperature" of the dive team with respect to human factors, and (2) identify initial areas of concern which may warrant further examination.*

Event data:

Date (mo./yr.): ....

Observer: ....

Command observed: ....

Equipment: ....
- Dive rig: ....
- Air/gas supply: ....

Dive scenario: ....
- Task: ....
- Depth: ....

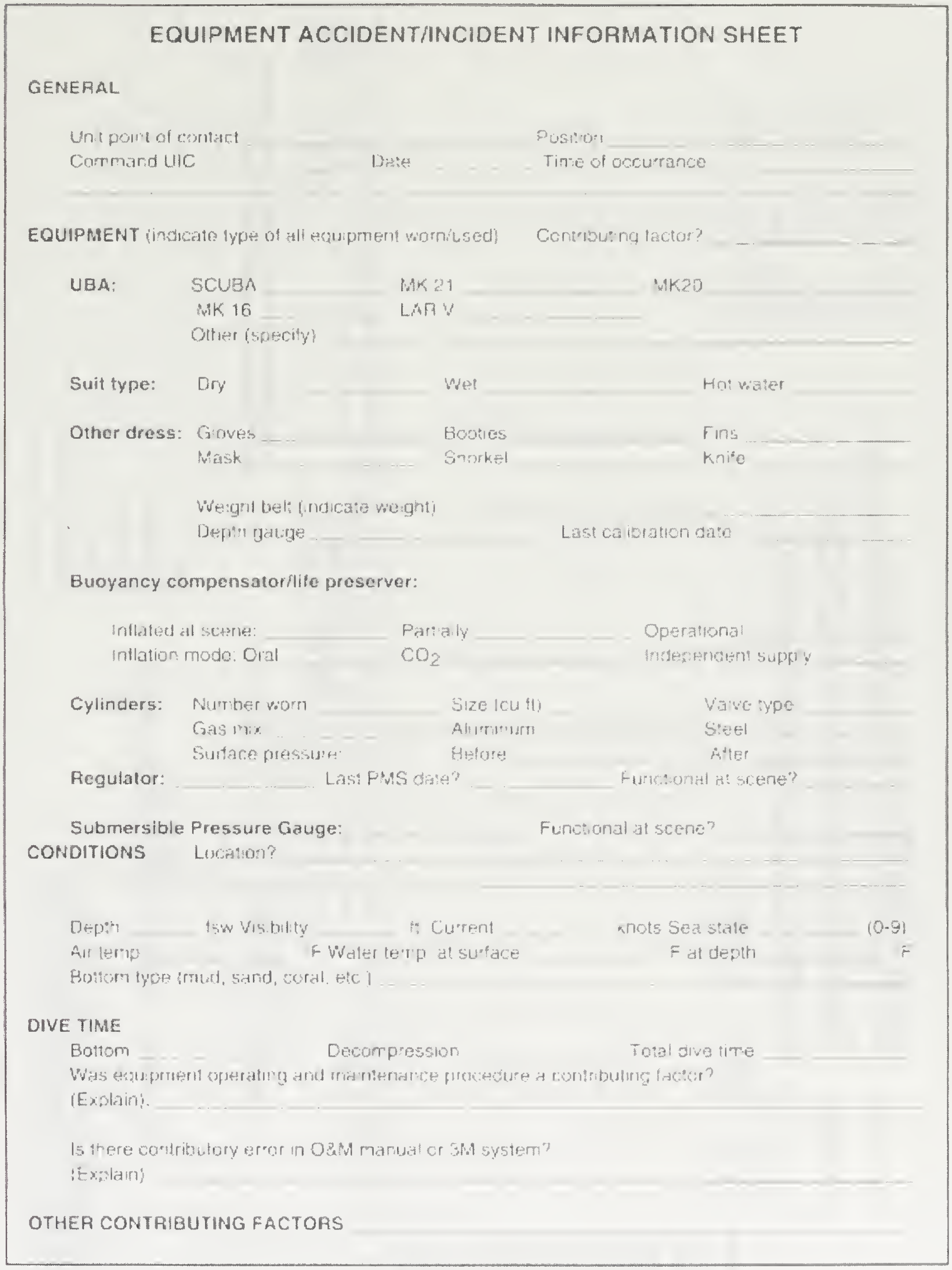
Temperature: ....
- air: ....
- water: ....

Surface conditions: ....
- swell: ....
- current: ....
- weather: ....

Bottom conditions: ....
- current: ....
- bottom type: ....
- temperature: ....
- visibility: ....

Dive team members: ....
- Dive supervisor: ....
- Diver #1: ....
- Diver #2 ....
- Standby diver: ....
- Tenders for #1: ....
- Tenders for #2: ....
- Communications: ....
- Charts: ....
- MDV: ....
- Diving Officer: ....

APPENDIX C: U.S. Navy Accident/Incident Information Sheet



EQUIPMENT ACCIDENT/INCIDENT INFORMATION SHEET

GENERAL

Unit point of contact ______ Position ______
Command UIC ______ Date ______ Time of occurrance ______

EQUIPMENT (indicate type of all equipment worn/used) Contributing factor? ______

UBA: SCUBA ______ MK 21 ______ MK20 ______
MK 16 ______ LAR V ______
Other (specify) ______

Suit type: Dry ______ Wet ______ Hot water ______

Other dress: Gloves ______ Booties ______ Fins ______
Mask ______ Snorkel ______ Knife ______

Weight belt (indicate weight) ______
Depth gauge ______ Last calibration date ______

Buoyancy compensator/life preserver:

Inflated at scene: ______ Partially ______ Operational ______
Inflation mode: Oral ______ CO_2 ______ Independent supply ______

Cylinders: Number worn ______ Size (cu ft) ______ Valve type ______
Gas mix ______ Aluminum ______ Steel ______
Surface pressure: Before ______ After ______

Regulator: ______ Last PMS date? ______ Functional at scene? ______

Submersible Pressure Gauge: ______ Functional at scene? ______

CONDITIONS Location? ______

Depth ______ fsw Visibility ______ ft Current ______ knots Sea state ______ (0-9)
Air temp ______ F Water temp at surface ______ F at depth ______ F
Bottom type (mud, sand, coral, etc.) ______

DIVE TIME

Bottom ______ Decompression ______ Total dive time ______
Was equipment operating and maintenance procedure a contributing factor?
(Explain). ______

Is there contributory error in O&M manual or 3M system?
(Explain) ______

OTHER CONTRIBUTING FACTORS ______

APPENDIX D: ADC Incident Data Reporting Form

ASSOCIATION OF DIVING CONTRACTORS
INCIDENT DATA REPORTING FORM

PERSON COMPLETING FORM	
COMPANY	
TITLE/POSITION	
DATE COMPLETED:	
PHONE:	

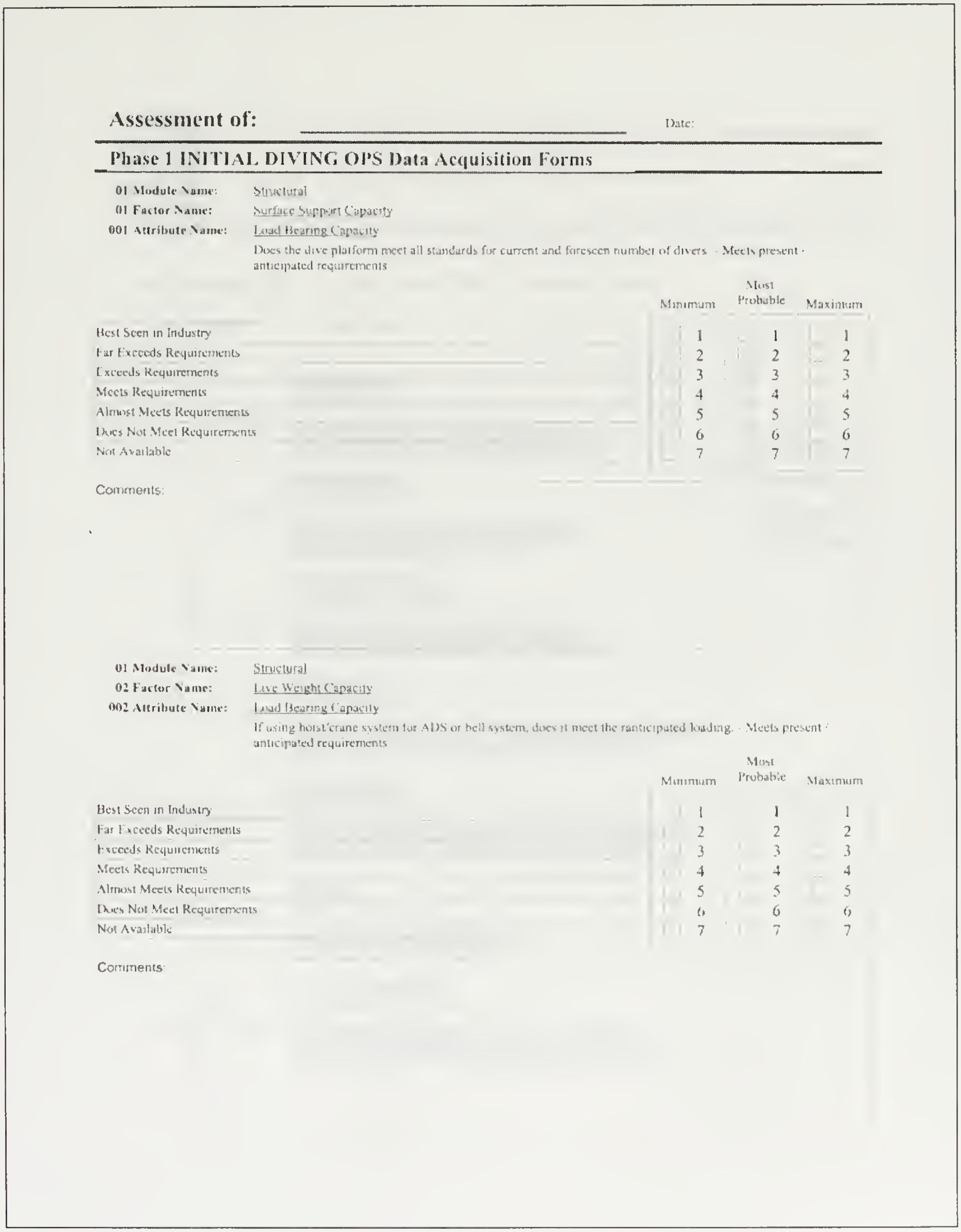
INCIDENT RATE = NUMBER OF INJURIES/ILLNESS X 200,000 / HOURS WORKED

	ON SITE DIVING OPERATIONS WITHIN NORTH AMERICAN WATERS UNDER COAST GUARD/OSHA JURISDICTION										OSHA/COAST GUARD RECORDABLE INCIDENTS TOTAL COMPANY FOR ALL NORTH AMERICAN DIVISIONS						
								INCIDENCE RATES FOR DIVING OPERATIONS							INCIDENCE RATES COMPANY WIDE		
	FATALITIES	LOST TIME	RESTRICTED ACTIVITY	NOW DISABLING	TYPE I OCS PAIN ONLY SEE NOTE 1	TYPE II OCS SERIOUS SEE NOTE 2	TOTAL DIVES SEE NOTE 3	LOST TIME	TOTAL RECORDABLE	DIVING OP's TOTAL HOUR's WORKED YEAR OR YTD	FATALITIES	LOST TIME ACCIDENTS	RESTRICTED ACTIVITY	NON DISABLING	LOST TIME	TOTAL RECORDABLE	COMPANY WIDE TOTAL HOUR's WORKED YEAR OR YTD
SECTION I INCIDENT HISTORY PAST YEAR 19 ___																	
SECTION II INCIDENT HISTORY PAST YEAR 19 ___																	
SECTION III INCIDENT HISTORY PAST YEAR 19 ___																	

DEFINITIONS:	LAST YEAR:	JANUARY 1, 19 ___	THRU DECEMBER 31, 19 ___
	PAST YEAR:	JANUARY 1, 19 ___	THRU DECEMBER 31, 19 ___
	RECORDABLE INCIDENT	AN ACCIDENT OR WORK RELATED ILLNESS REQUIRING TREATMENT BY A LICENSED PHYSICIAN AS DEFINED BY THE OSHA RECORDKEEPING GUIDELINES FOR OCCUPATIONAL INJURIES & ILLNESS (September 1995)	
	LOST TIME INCIDENT	A WORK RELATED ACCIDENT OR ILLNESS THAT RESULTS IN AN EMPLOYEE BEING UNABLE TO PERFORM ANY WORK FOR 24 HOURS OR MORE, NOT COUNTING THE DAY OF THE ACCIDENT OR THE DAY HE RETURNS TO WORK	
	RESTRICTED ACTIVITY	A WORK RELATED ACCIDENT OR ILLNESS THAT RESULTS IN AN EMPLOYEE BEING UNABLE TO PERFORM THE FULL RANGE OF DUTIES ASSIGNED TO HIM FOR THAT JOB FOR 24 HOURS OR MORE, NOT COUNTING THE DAY OF THE INCIDENT OR THE DAY HE RETURNS TO WORK	

NOTE 1	NOTE 2	NOTE 3
SYMPTOMS RESOLVED ON SITE DO NOT INCLUDE IN NON DISABLING COLUMN	IF NO ON SHORE TREATMENT CLASSIFY AS RESTRICTED ACTIVITY OTHERWISE LOST TIME	ONE DIVE L/S TO R/S FOR SAT DIVES COUNT NUMBER OF MAN DAYS SEAL TO SEAL

APPENDIX E: Initial Diving Ops Safety Management Assessment (Phase 1)



Assessment of: ______________________ Date:

Phase 1 INITIAL DIVING OPS Data Acquisition Forms

01 Module Name: Structural
01 Factor Name: Surface Support Capacity
001 Attribute Name: Load Bearing Capacity

Does the dive platform meet all standards for current and foreseen number of divers - Meets present / anticipated requirements

	Minimum	Most Probable	Maximum
Best Seen in Industry	1	1	1
Far Exceeds Requirements	2	2	2
Exceeds Requirements	3	3	3
Meets Requirements	4	4	4
Almost Meets Requirements	5	5	5
Does Not Meet Requirements	6	6	6
Not Available	7	7	7

Comments:

01 Module Name: Structural
02 Factor Name: Live Weight Capacity
002 Attribute Name: Load Bearing Capacity

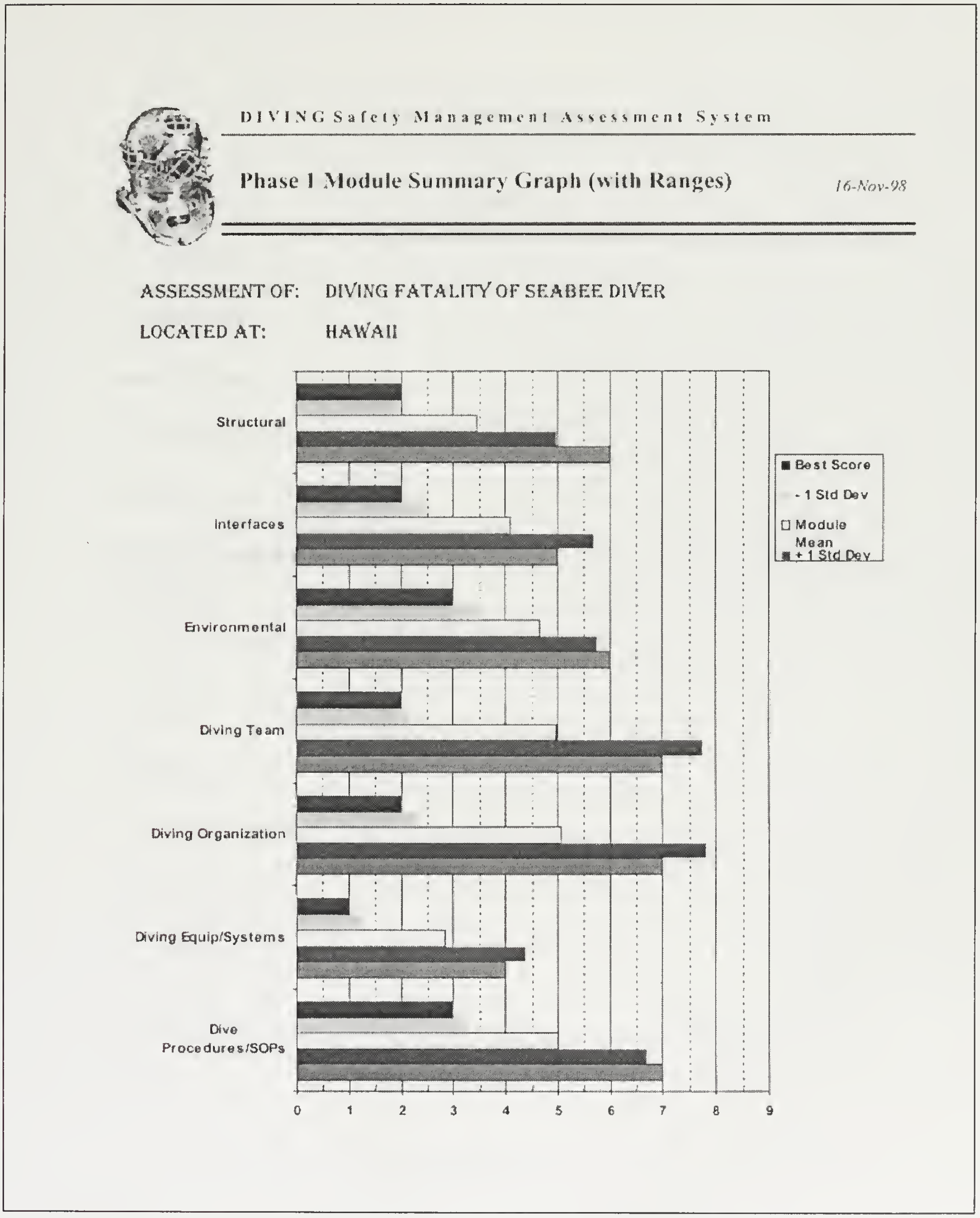
If using hoist/crane system for ADS or bell system, does it meet the ranticipated loading. - Meets present / anticipated requirements

	Minimum	Most Probable	Maximum
Best Seen in Industry	1	1	1
Far Exceeds Requirements	2	2	2
Exceeds Requirements	3	3	3
Meets Requirements	4	4	4
Almost Meets Requirements	5	5	5
Does Not Meet Requirements	6	6	6
Not Available	7	7	7

Comments:

]

APPENDIX F: Sample Phase 1 Module Summary for U.S. Navy Fatality



DIVING Safety Management Assessment System

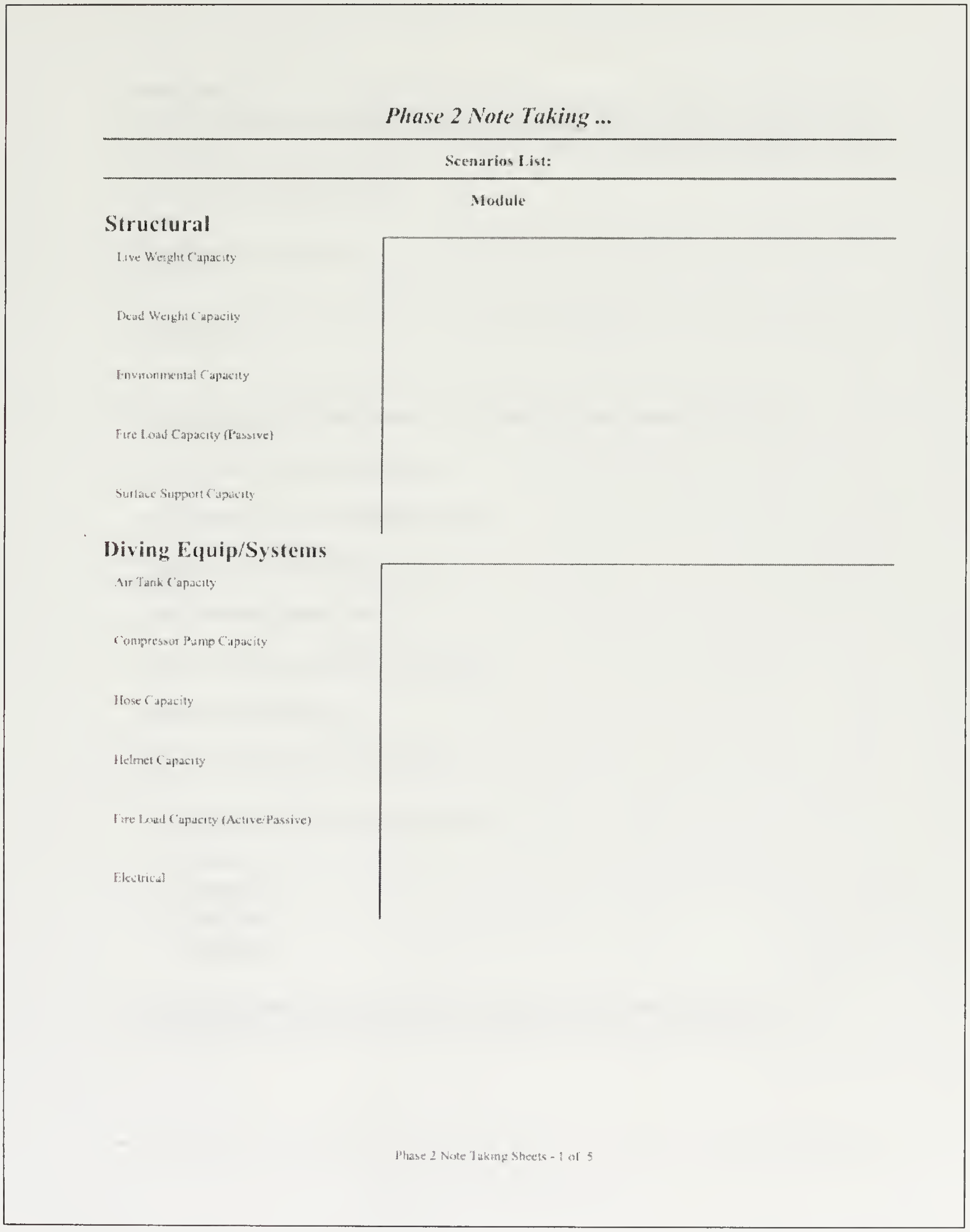
Phase 1 Module Summary Graph (with Ranges)

16-Nov-98

ASSESSMENT OF: DIVING FATALITY OF SEABEE DIVER

LOCATED AT: HAWAII

APPENDIX G: Phase 2 Detailed Assessment Notes



Phase 2 Note Taking ...

Scenarios List:

Module

Structural

Live Weight Capacity

Dead Weight Capacity

Environmental Capacity

Fire Load Capacity (Passive)

Surface Support Capacity

Diving Equip/Systems

Air Tank Capacity

Compressor Pump Capacity

Hose Capacity

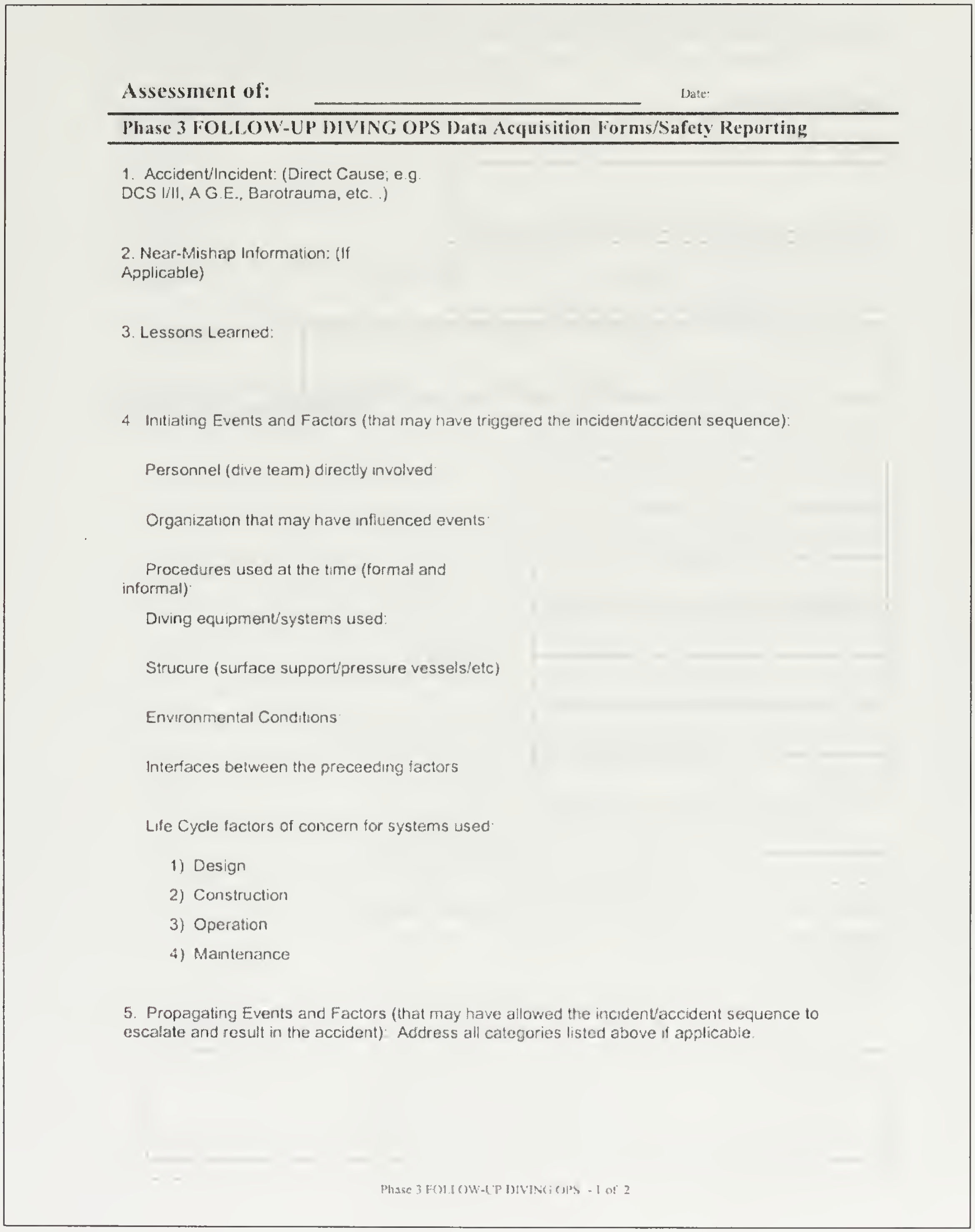
Helmet Capacity

Fire Load Capacity (Active/Passive)

Electrical

Phase 2 Note Taking Sheets - 1 of 5

APPENDIX H: Follow-up Diving Ops Safety Management Assessment (Phase 3)



Assessment of: ______________________ Date:

Phase 3 FOLLOW-UP DIVING OPS Data Acquisition Forms/Safety Reporting

1. Accident/Incident: (Direct Cause; e.g. DCS I/II, A.G.E., Barotrauma, etc. .)

2. Near-Mishap Information: (If Applicable)

3. Lessons Learned:

4. Initiating Events and Factors (that may have triggered the incident/accident sequence):

Personnel (dive team) directly involved:

Organization that may have influenced events:

Procedures used at the time (formal and informal):

Diving equipment/systems used:

Strucure (surface support/pressure vessels/etc)

Environmental Conditions:

Interfaces between the preceeding factors

Life Cycle factors of concern for systems used:

1) Design
2) Construction
3) Operation
4) Maintenance

5. Propagating Events and Factors (that may have allowed the incident/accident sequence to escalate and result in the accident): Address all categories listed above if applicable.

Phase 3 FOLLOW-UP DIVING OPS - 1 of 2

Assessment of: ____________________ Date:

Phase 3 FOLLOW-UP DIVING OPS Data Acquisition Forms/Safety Reporting

6. Contributing Events and Factors (that may have encouraged the initiating and propagating events): Address all categories listed above if applicable.

7. Dive Times:

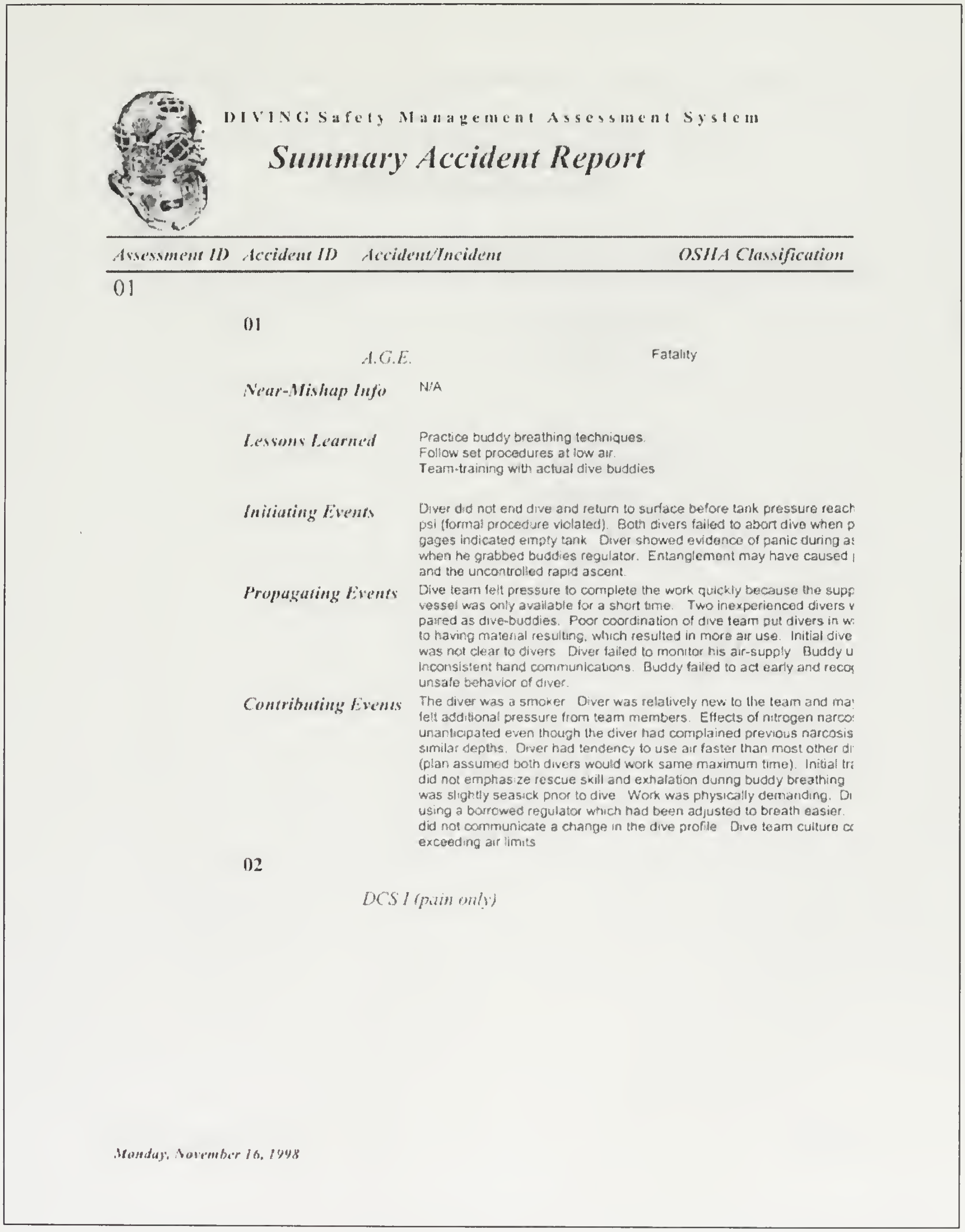
Bottom time: Decompression time: Total dive time:

Total time of Operation/Project: (To be completed at the completion of the project)

8. OSHA Classification of incident/accident: (e.g. Fatality, Lost Time, Restricted Activity, Non-disabling)

Phase 3 FOLLOW-UP DIVING OPS - 2 of 2

APPENDIX I: Sample Monthly Safety Report (generated from DSMAS)



DIVING Safety Management Assessment System

Summary Accident Report

Assessment ID	*Accident ID*	*Accident/Incident*	*OSHA Classification*
01			
	01		
		A.G.E.	Fatality

Near-Mishap Info N/A

Lessons Learned

Practice buddy breathing techniques.
Follow set procedures at low air.
Team-training with actual dive buddies

Initiating Events

Diver did not end dive and return to surface before tank pressure reach
psi (formal procedure violated). Both divers failed to abort dive when p
gages indicated empty tank Diver showed evidence of panic during as
when he grabbed buddies regulator. Entanglement may have caused
and the uncontrolled rapid ascent.

Propagating Events

Dive team felt pressure to complete the work quickly because the supp
vessel was only available for a short time. Two inexperienced divers
paired as dive-buddies. Poor coordination of dive team put divers in w
to having material resulting, which resulted in more air use. Initial dive
was not clear to divers Diver failed to monitor his air-supply Buddy u
Inconsistent hand communications. Buddy failed to act early and reco
unsafe behavior of diver.

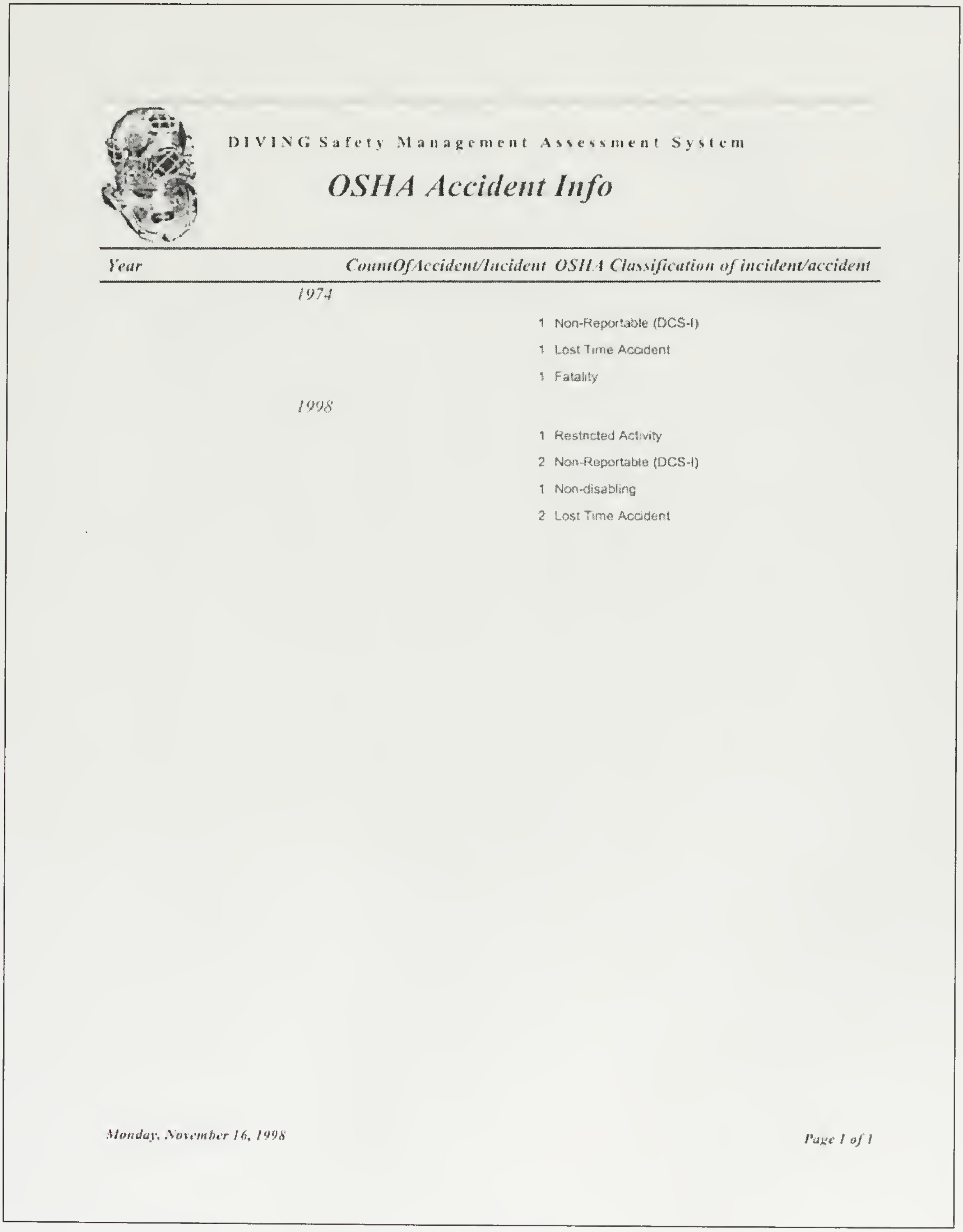
Contributing Events

The diver was a smoker Diver was relatively new to the team and ma
felt additional pressure from team members. Effects of nitrogen narco
unanticipated even though the diver had complained previous narcosis
similar depths. Diver had tendency to use air faster than most other di
(plan assumed both divers would work same maximum time). Initial tr
did not emphasize rescue skill and exhalation during buddy breathing
was slightly seasick prior to dive Work was physically demanding. D
using a borrowed regulator which had been adjusted to breath easier.
did not communicate a change in the dive profile Dive team culture c
exceeding air limits

Assessment ID	*Accident ID*	*Accident/Incident*	*OSHA Classification*
	02		
		DCS I (pain only)	

Monday, November 16, 1998

APPENDIX J: Sample OSHA Accident Input Report (generated from DSMAS)



DIVING Safety Management Assessment System

OSHA Accident Info

Year	*CountOfAccident/Incident*	*OSHA Classification of incident/accident*
1974		
	1	Non-Reportable (DCS-I)
	1	Lost Time Accident
	1	Fatality
1998		
	1	Restricted Activity
	2	Non-Reportable (DCS-I)
	1	Non-disabling
	2	Lost Time Accident

Monday, November 16, 1998

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APPENDIX K: DSMAS Disk

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